



(12) UK Patent (19) GB (11) 2 319 796 (13) B

(54) Title of Invention

Formation treatment method using deformable  
particles

(51) INT CL<sup>7</sup>; E21B 43/267

(21)	Application No <b>9725153.2</b>	(72)	Inventor(s) <b>Harold D Brannon</b> <b>Allan R Rickards</b> <b>Philip J Rae</b> <b>Gino A DiLullo</b>
(22)	Date of filing <b>27.11.1997</b>	(73)	Proprietor(s) <b>B.J. Services Company</b>  <b>(Incorporated in USA - Delaware)</b>  <b>5500 Northwest Central Drive</b> <b>Houston</b> <b>Texas 77092</b> <b>United States of America</b>
(30)	Priority Data		
(31)	<b>08/756414</b>		
(32)	<b>27.11.1996</b>		
(33)	<b>US</b>		
(60)	Parent of Application No(s) <b>0108236.1</b> under Section 15(4) of the Patents Act 1977	(74)	Agent and/or Address for Service <b>Forrester Ketley &amp; Co</b> <b>Forrester House</b> <b>52 Bounds Green Road</b> <b>London</b> <b>N11 2EY</b> <b>United Kingdom</b>
(43)	Application published <b>03.06.1998</b>		
(45)	Patent published <b>15.08.2001</b>		
(52)	Domestic classification (Edition S) <b>E1F FPA</b>		
(56)	Documents cited <b>EP0771935 A</b> <b>WO96/04464 A</b> <b>US5582249 A</b> <b>US5501274 A</b> <b>US5439055 A</b> <b>US4664619 A</b> <b>US3929191 A</b>		
(58)	Field of search  As for published application 2319796 A viz: UK CL(Edition P) E1F FPA FPB INT CL <sup>7</sup> E21B Online: WPI updated as appropriate		

11/16

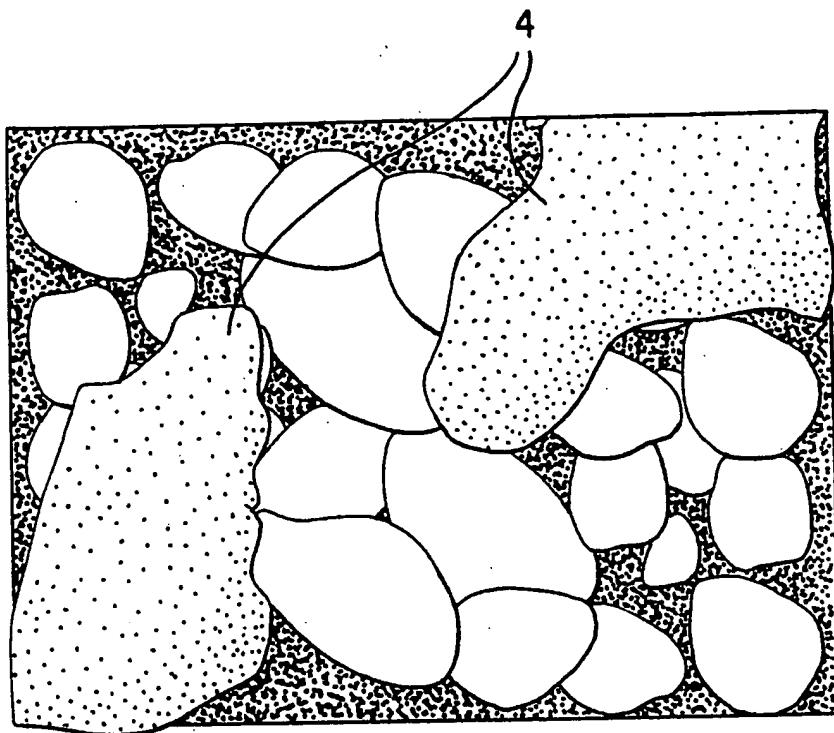


FIG. 2 PRIOR ART

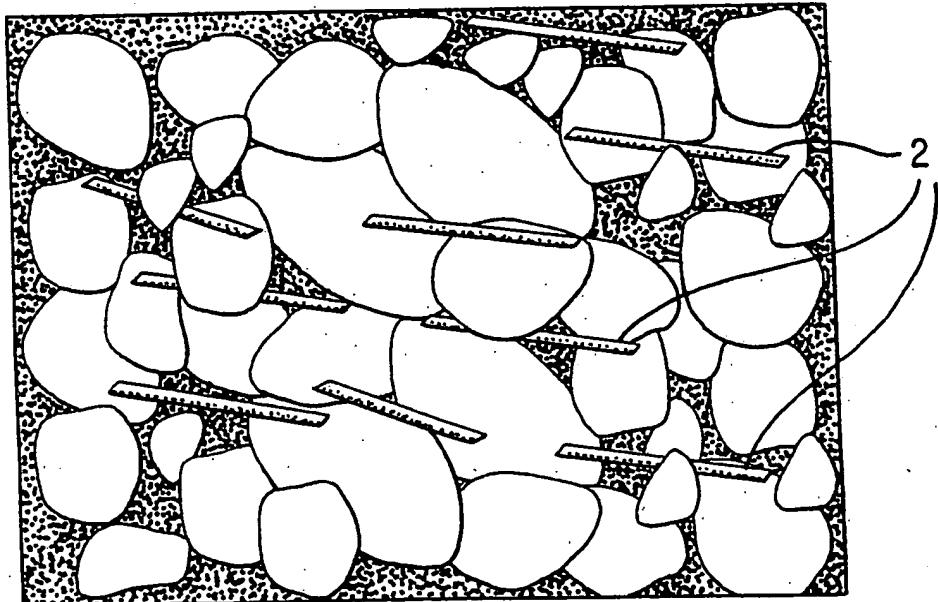


FIG. 1 PRIOR ART

2/16

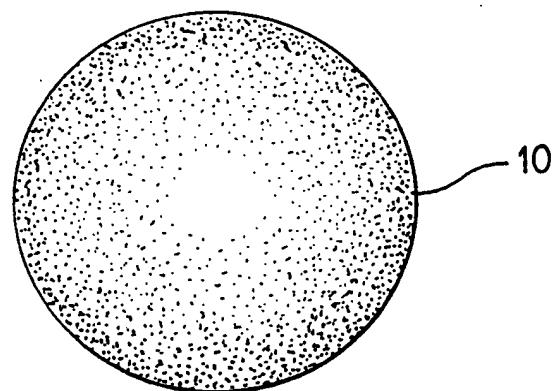


FIG. 3

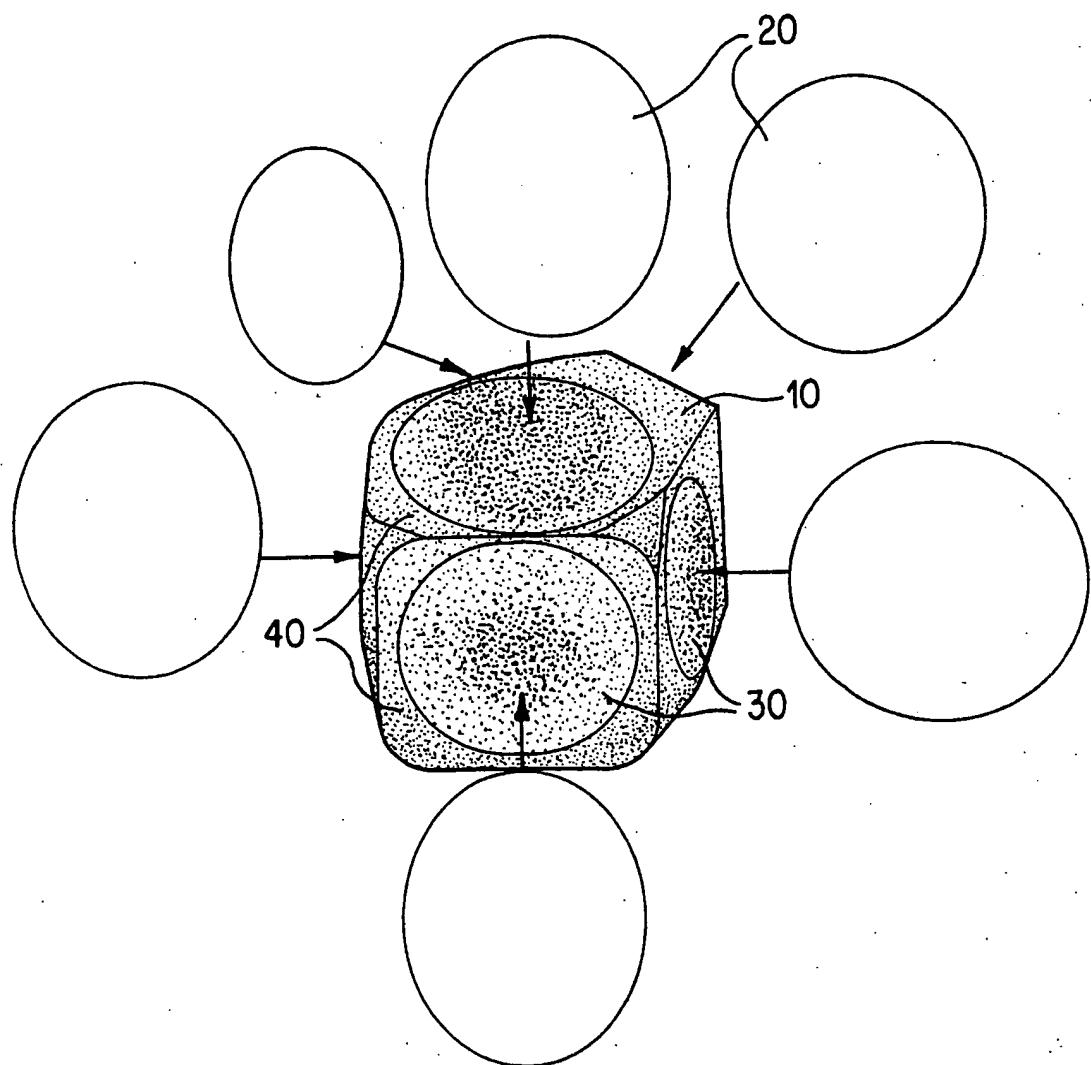


FIG. 4

3/16

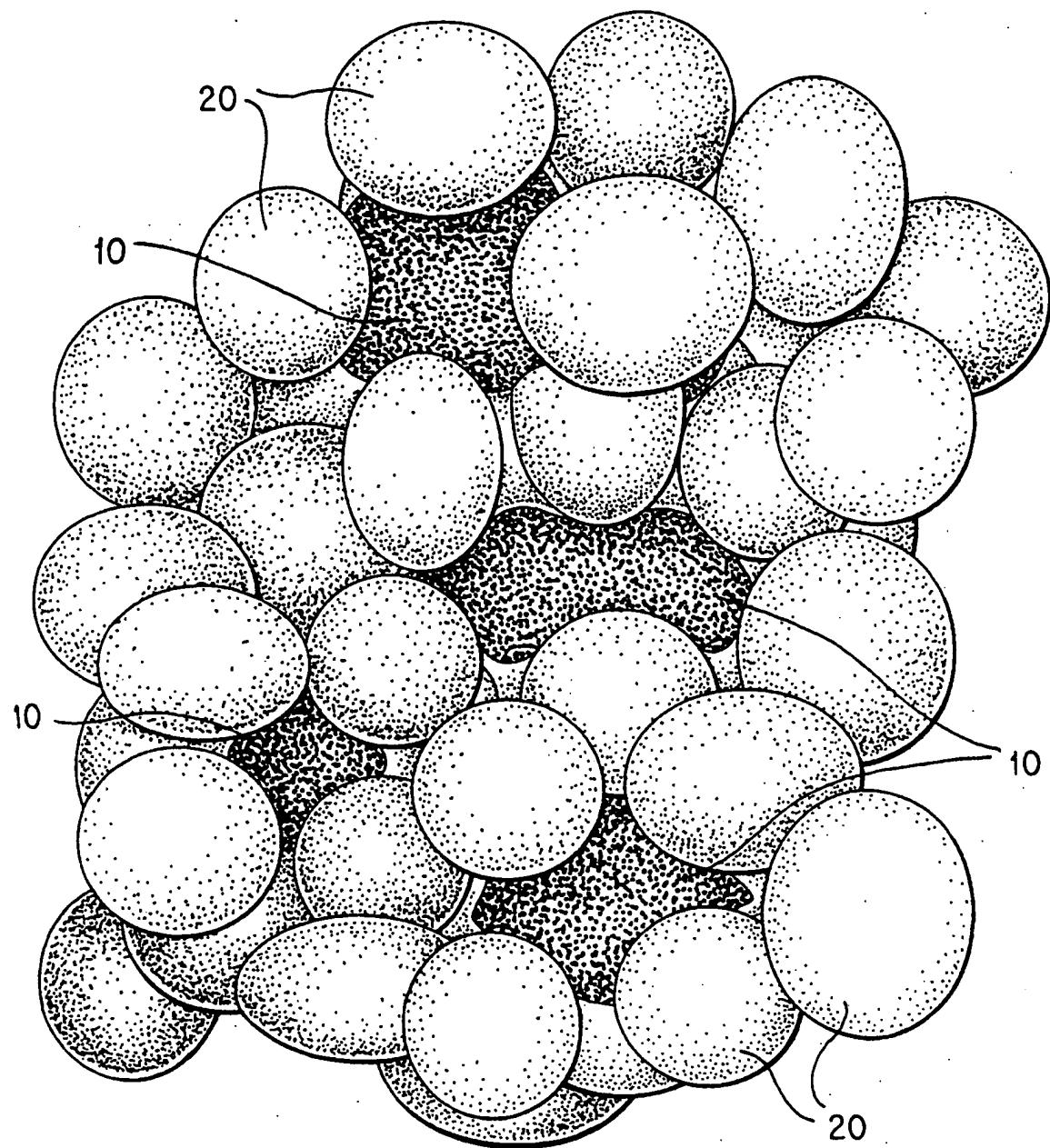


FIG. 5

4/16

FIG.8

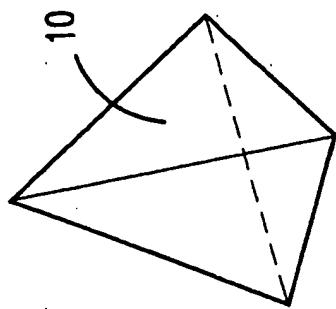


FIG.7

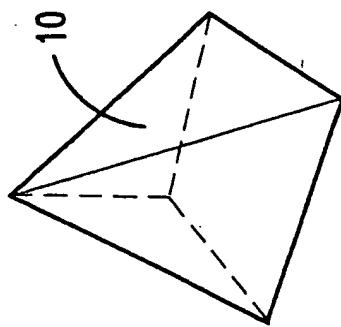


FIG.6

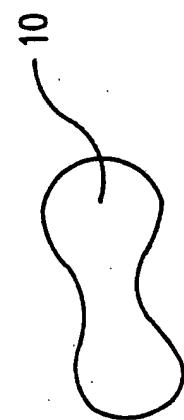
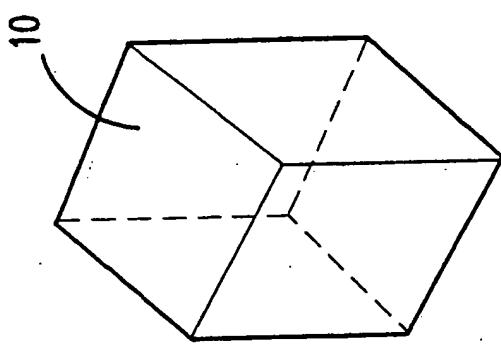


FIG.9

20/40 MESH PLASTIC BEADS  
STRESS VERSUS STRAIN FOR COMPACTION OF PSDVB PLASTIC BEADS

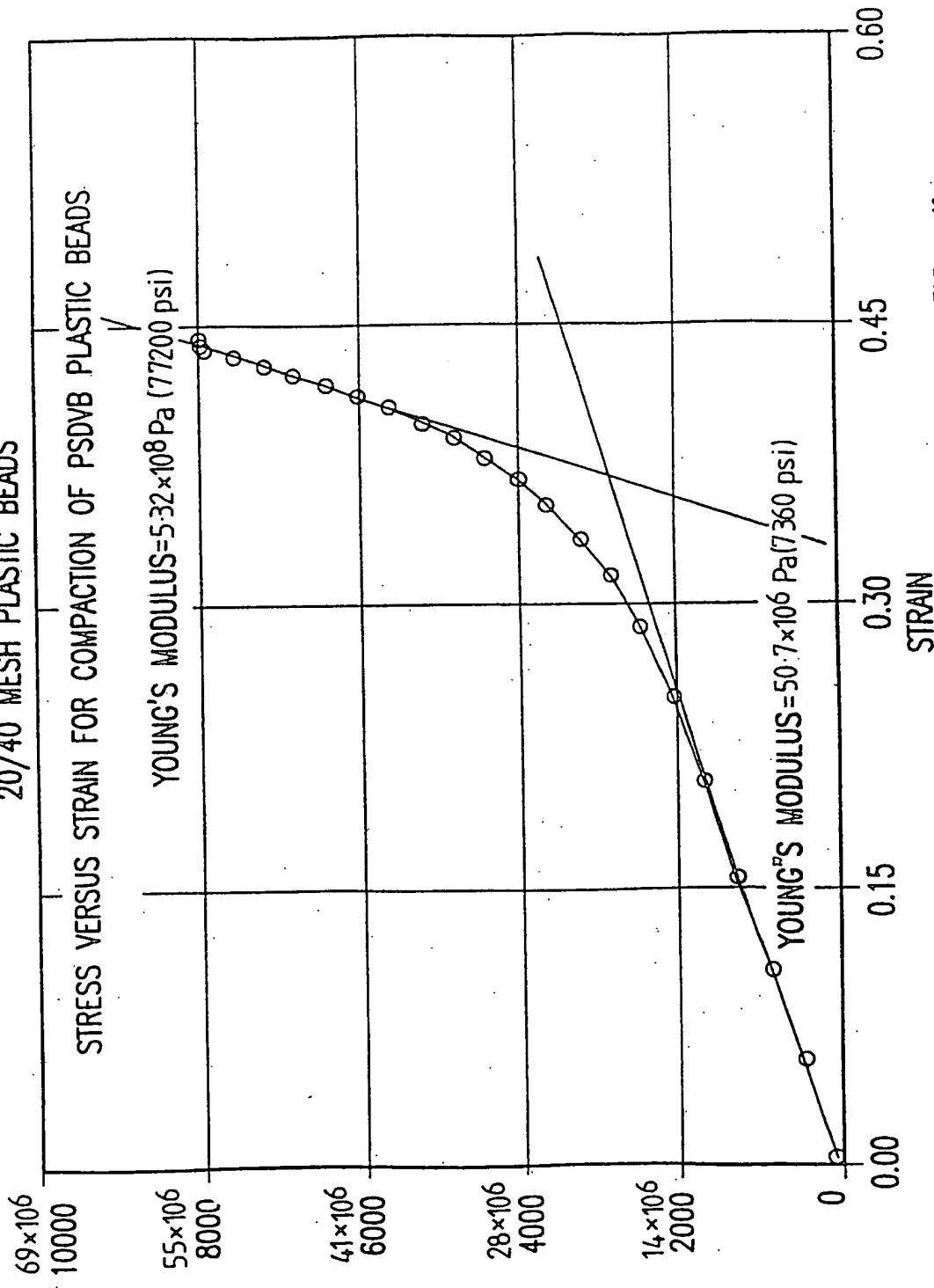
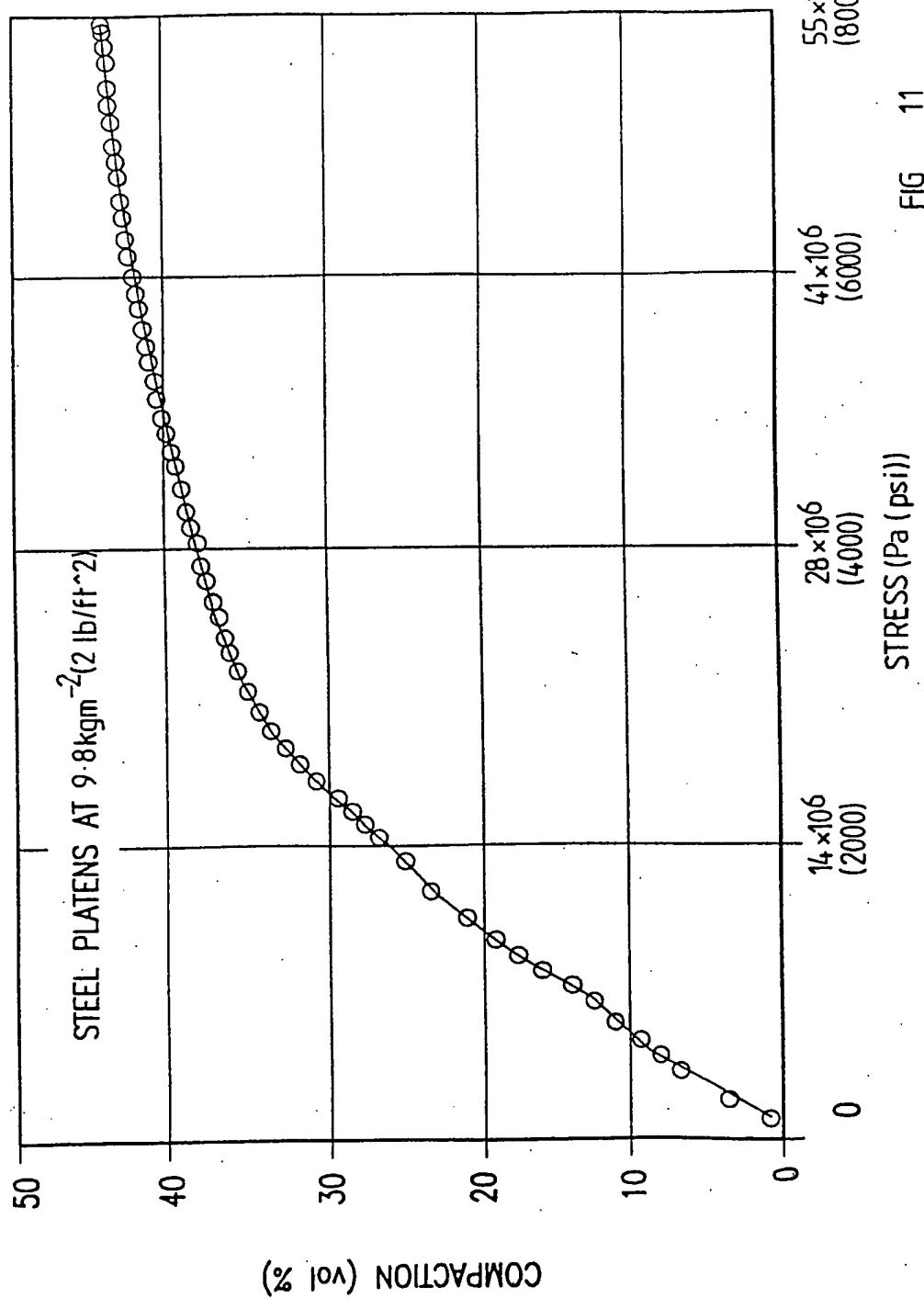


FIG 10

10/6



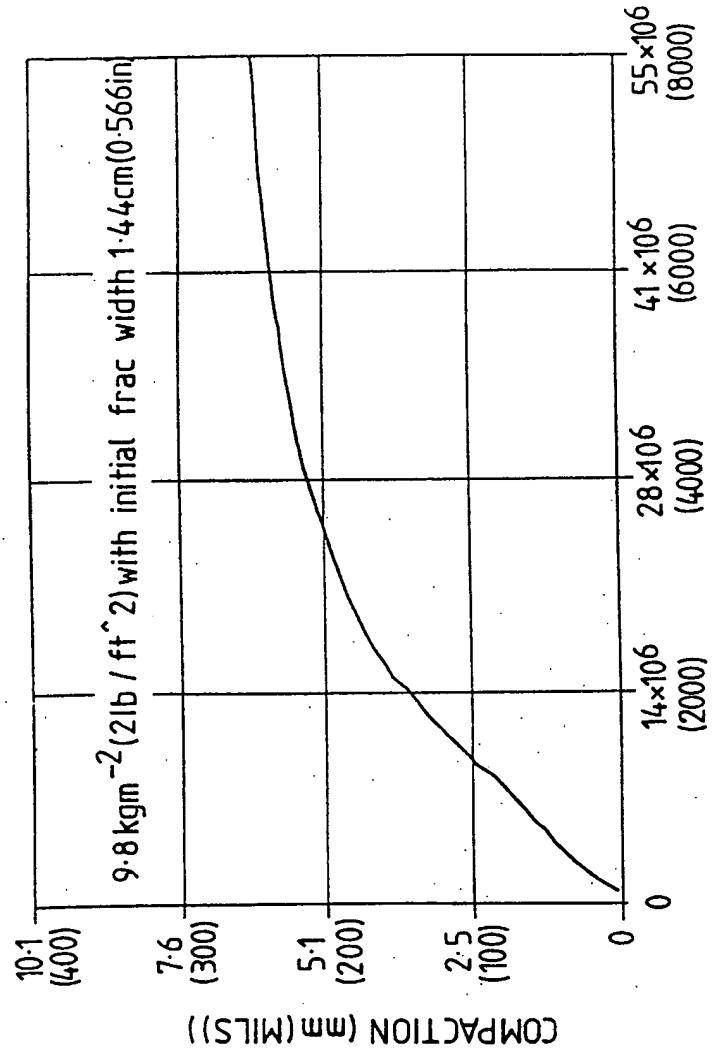
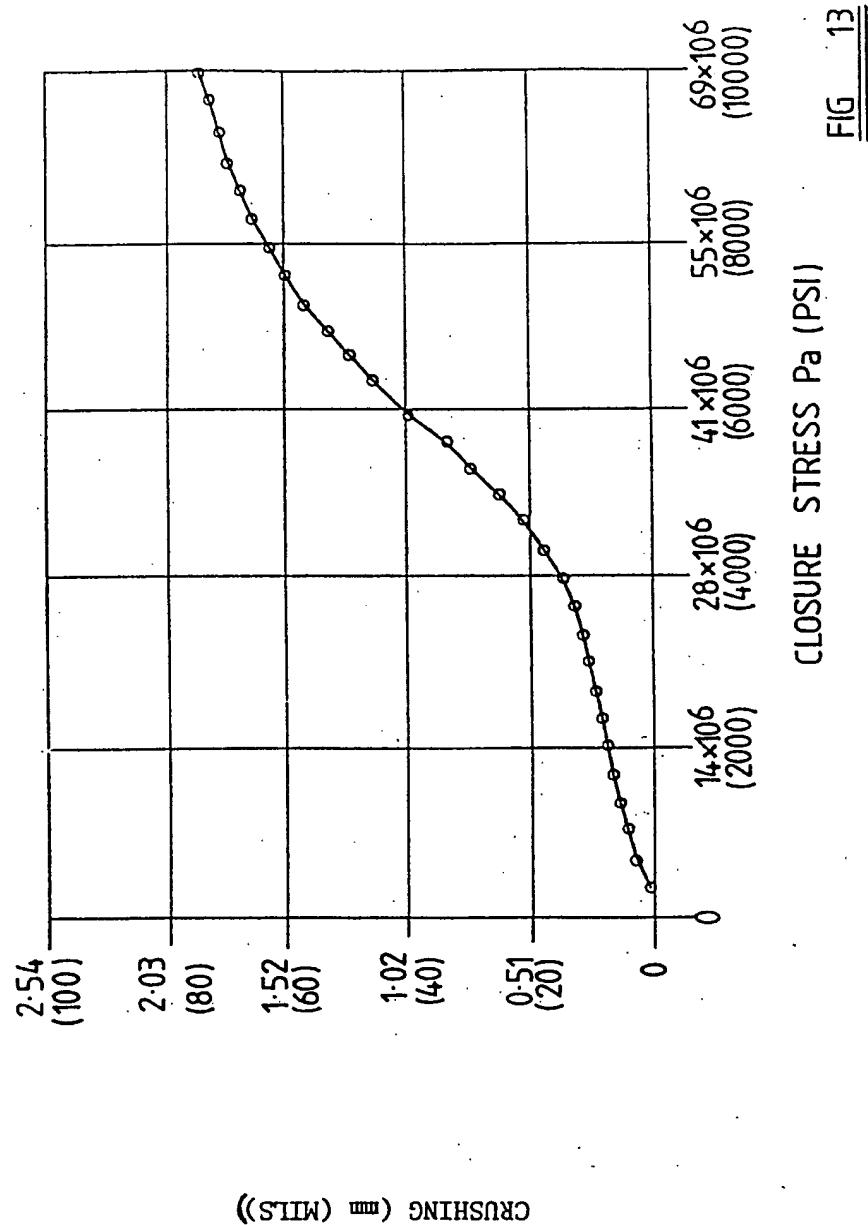


FIG 12

8/16



Y16

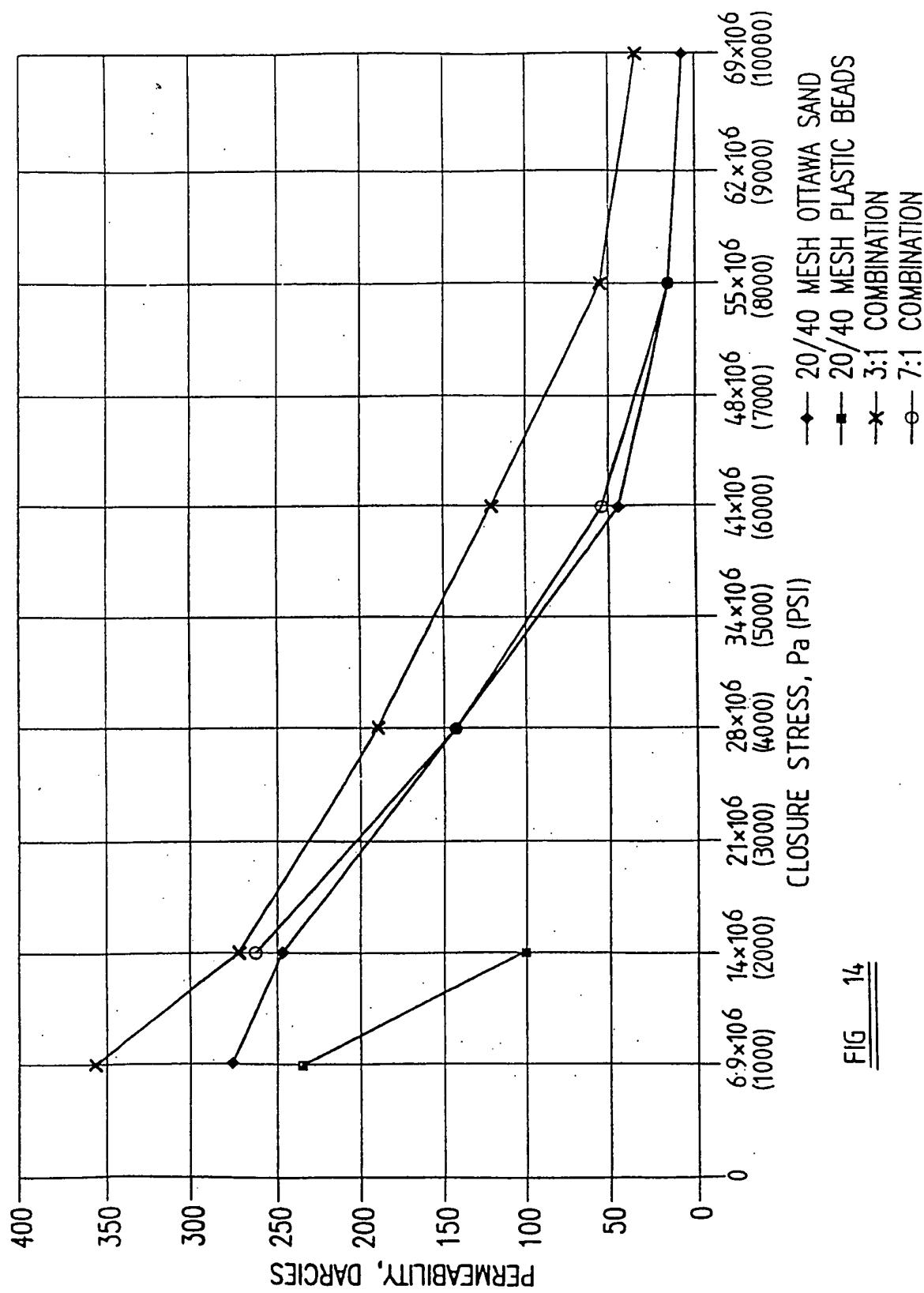


FIG 14

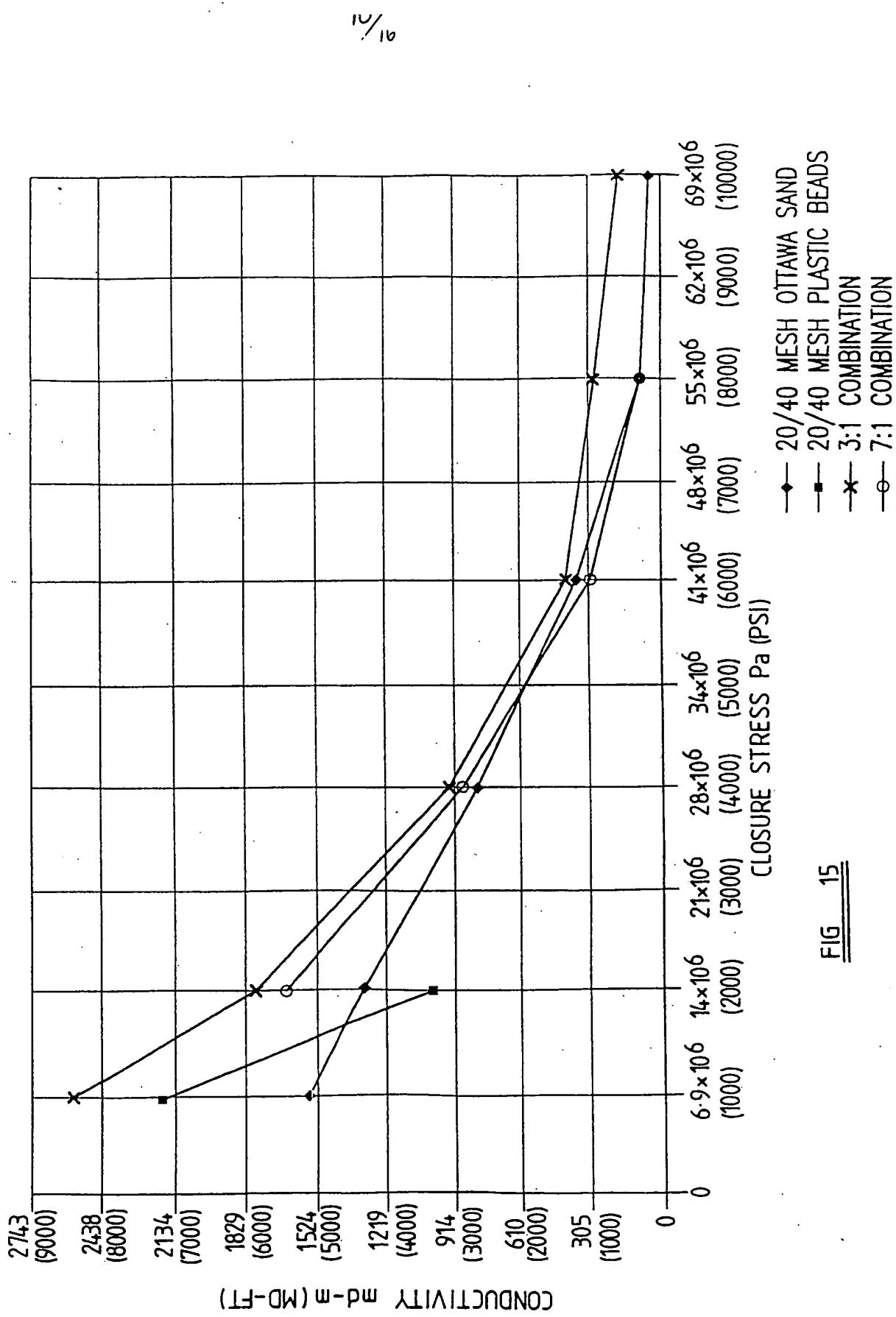


FIG 15

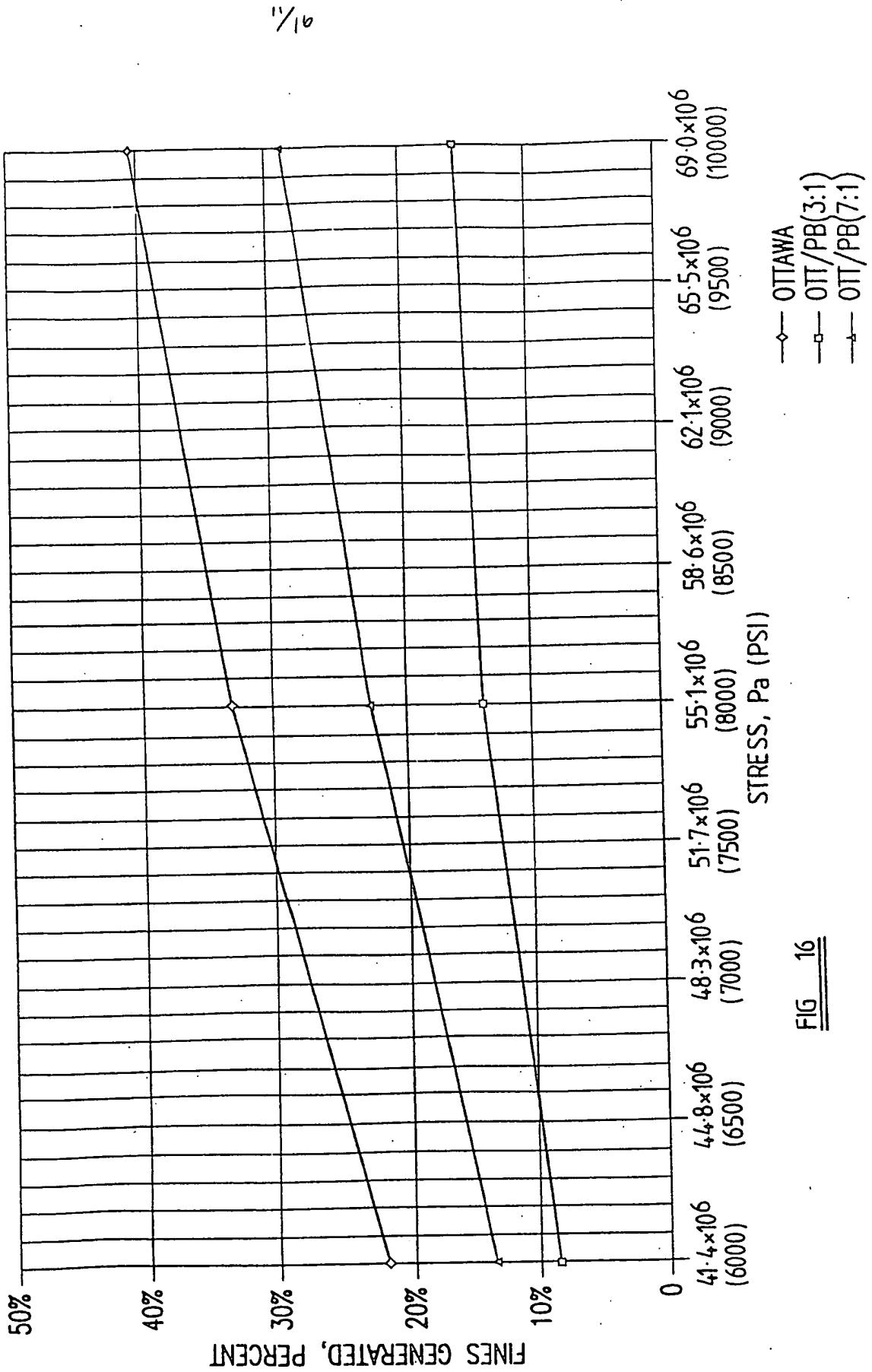


FIG 16

12/16

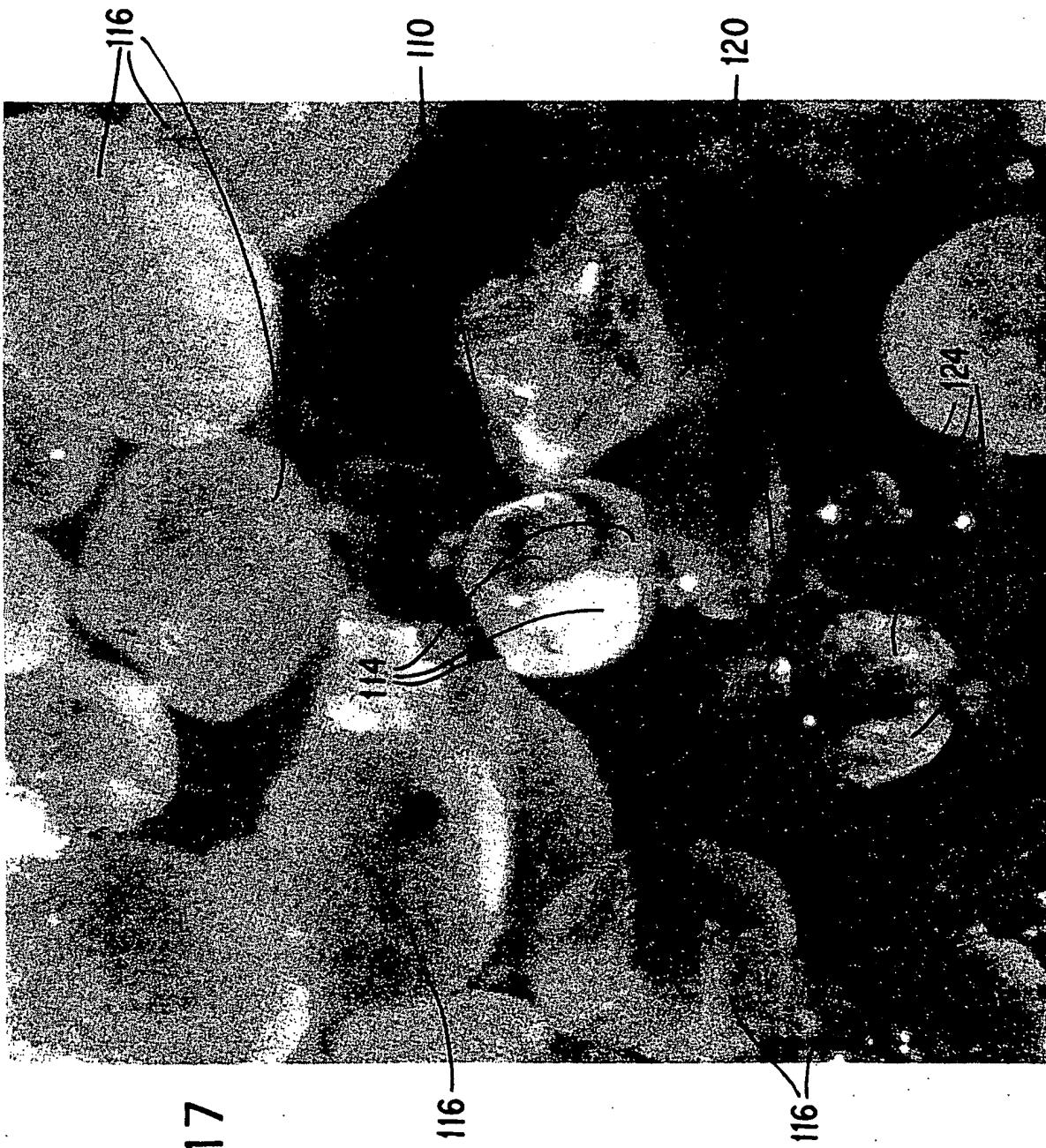


FIG. 17

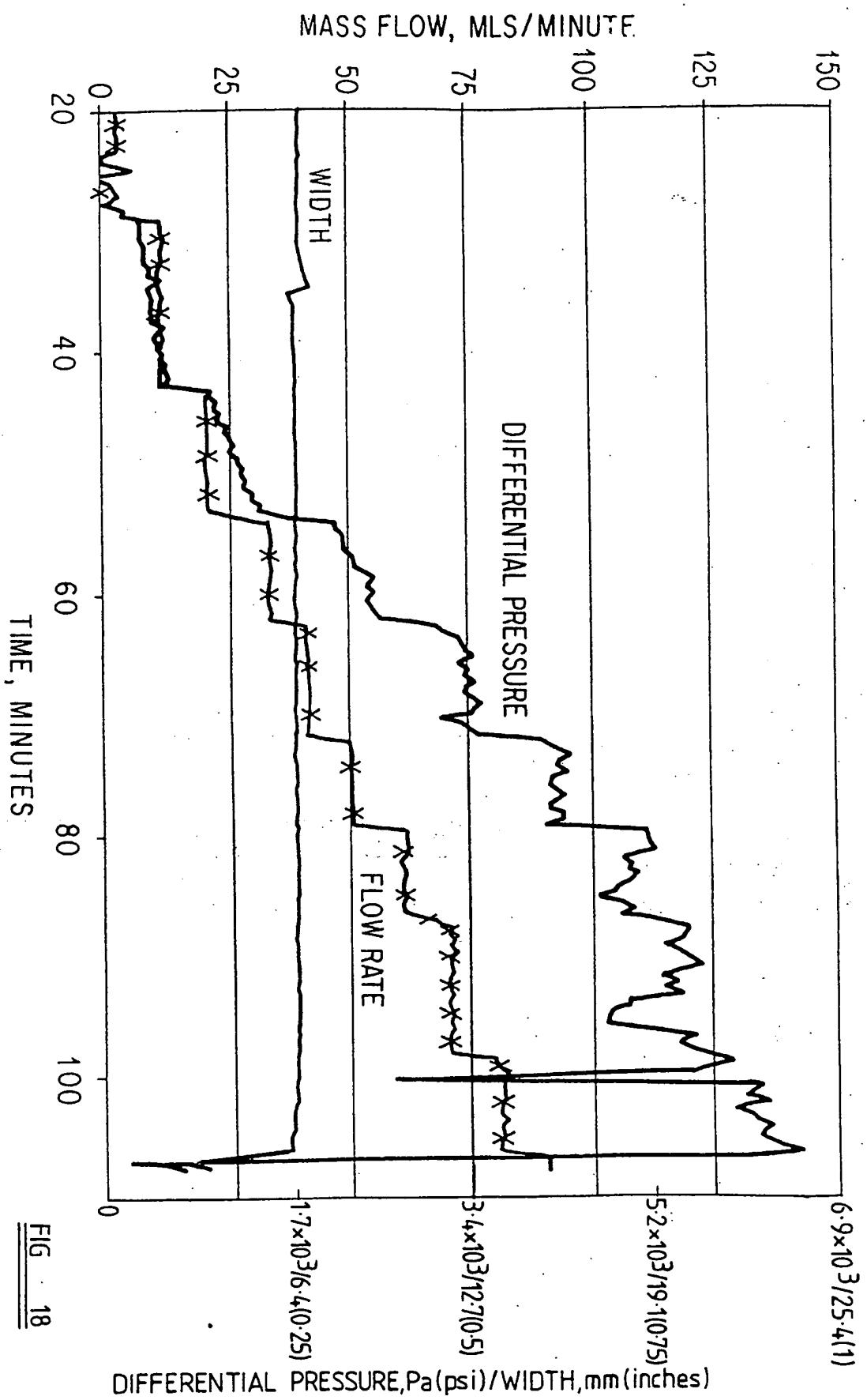


FIG 18

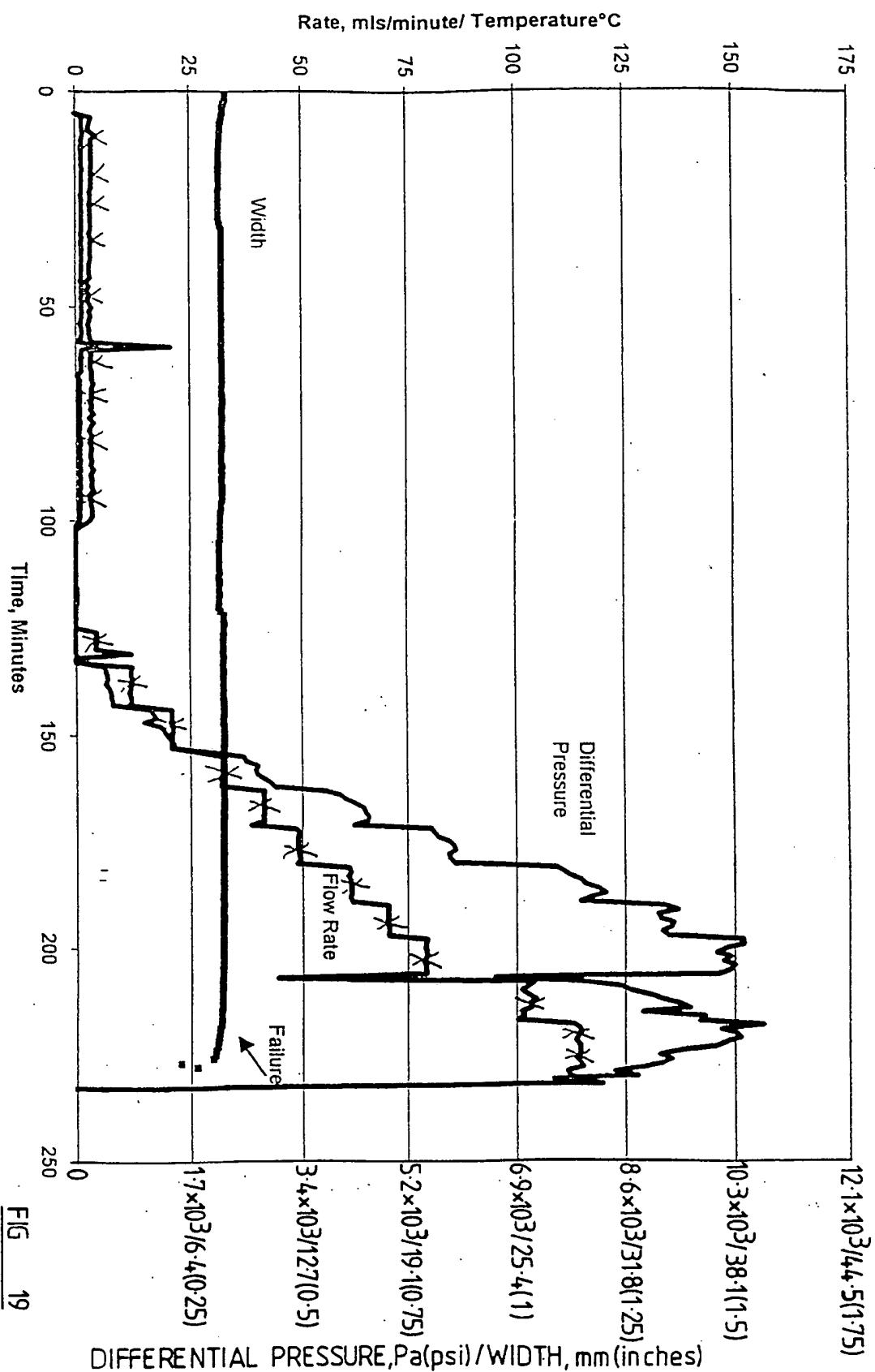


FIG 19

$12.1 \times 10^3 / 44.5 (1.75)$

$10.3 \times 10^3 / 38.1 (1.5)$

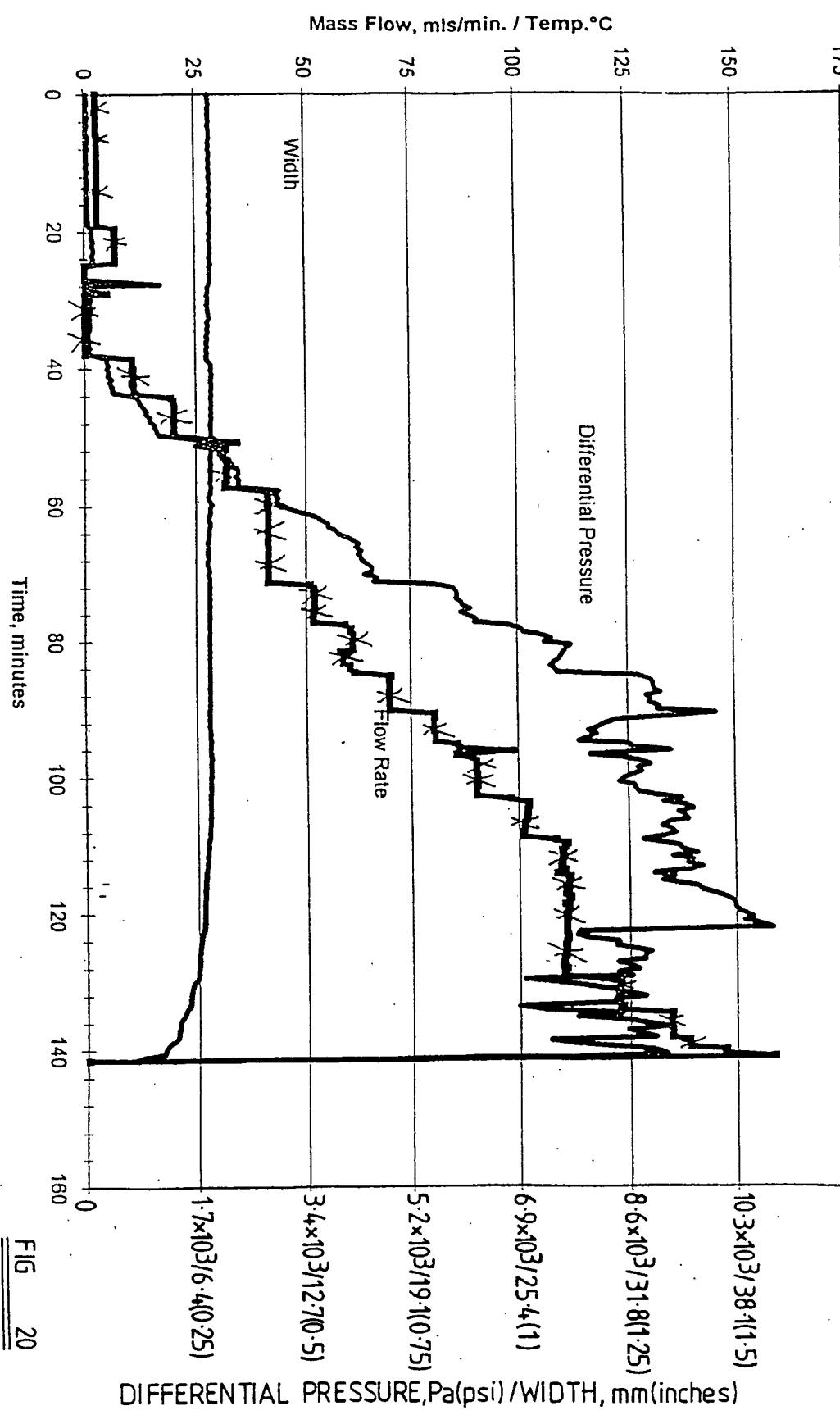
$8.6 \times 10^3 / 31.8 (1.25)$

$6.9 \times 10^3 / 25.4 (1)$

$5.2 \times 10^3 / 19.1 (0.75)$

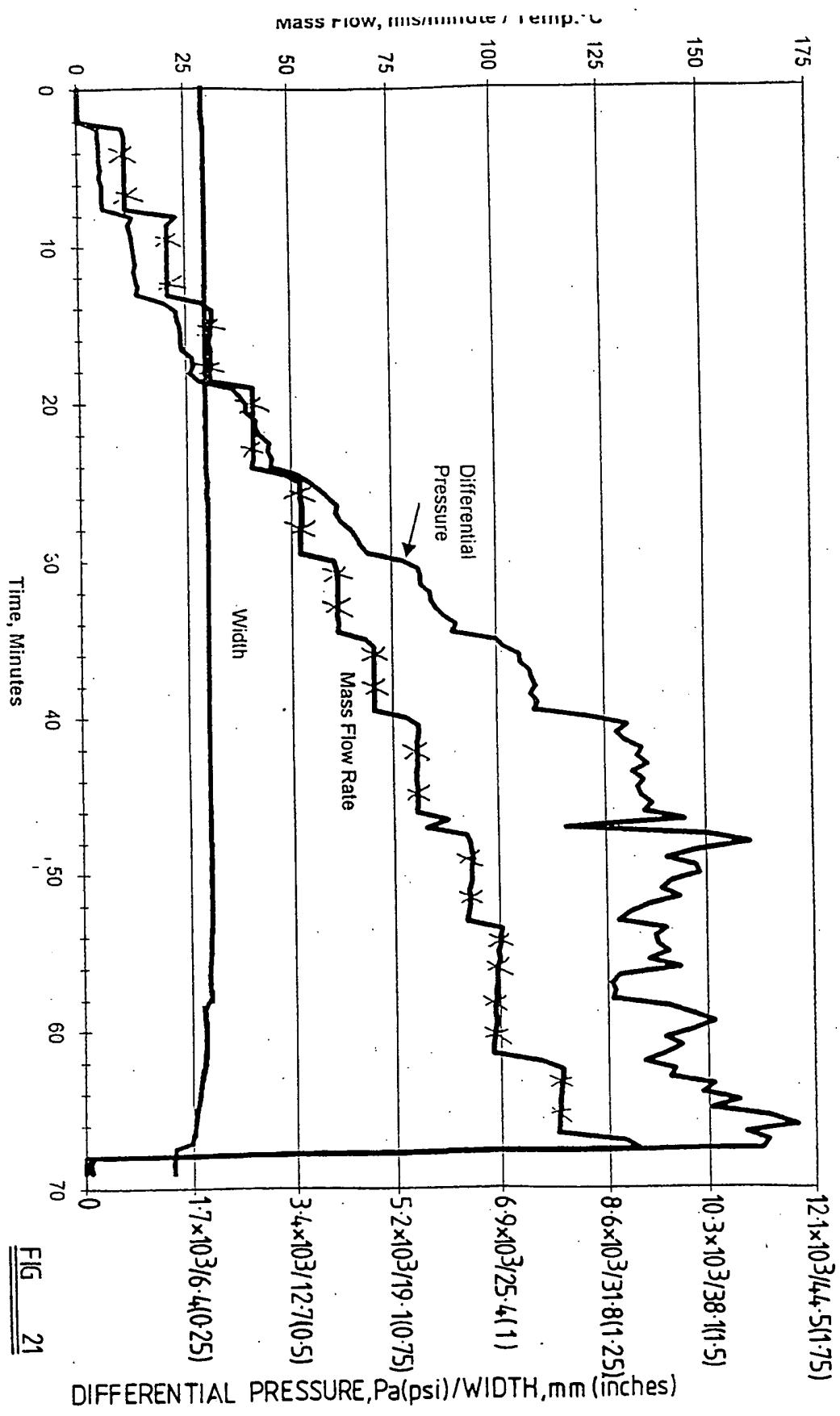
$3.4 \times 10^3 / 12.7 (0.5)$

$1.7 \times 10^3 / 6.4 (0.25)$



DIFFERENTIAL PRESSURE, Pa(psi) / WIDTH, mm(inches)

FIG 20



**Title of Invention:**

5

"FORMATION TREATMENT METHOD USING  
DEFORMABLE PARTICLES"

**Field of the Invention**

10

This invention relates generally to subterranean formation treatments and, more specifically, to hydraulic fracturing treatments for subterranean formations. In particular, this invention relates to deformable particles mixed with fracturing proppants to reduce fines generation, improve fracture conductivity, and/or minimize proppant flowback.

15

**Description of the Related Art**

Hydraulic fracturing is a common stimulation technique used to enhance production of fluids from subterranean formations. In a typical hydraulic fracturing treatment, fracturing treatment fluid containing a solid proppant material is injected into the formation at a pressure sufficiently high enough to cause the formation or enlargement of fractures in the reservoir. During a typical fracturing treatment, proppant material is deposited in a fracture, where it remains after the treatment is completed. After deposition, the proppant material serves to hold the fracture open, thereby enhancing the ability of fluids to migrate from the formation to the well bore through the fracture. Because fractured well productivity depends on the ability of a fracture to conduct fluids from a formation to a wellbore, fracture conductivity is an important parameter in determining the degree of success of a hydraulic fracturing treatment.

One problem related to hydraulic fracturing treatments is the creation of reservoir "fines" and associated reduction in fracture conductivity. These fines may be produced when proppant materials are subjected to reservoir closure stresses within a formation fracture which cause proppant materials to be compressed together in such a way that small particles ("fines") are generated from the proppant material and/or reservoir matrix. In some cases, production of fines may be exacerbated during production/workover operations when a well is shut-in and then

opened up. This phenomenon is known as "stress cycling" and is believed to result from increased differential pressure and closure stress that occurs during fluid production following a shut-in period. Production of fines is undesirable because of particulate production problems, and because of reduction in reservoir permeability due to plugging of pore throats in the 5 reservoir and/or proppant pack matrix.

Production of particulate solids with subterranean formation fluids is also a common problem. The source of these particulate solids may be unconsolidated material from the formation, proppant from a fracturing treatment and/or fines generated from crushed fracture 10 proppant, as mentioned above. Production of solid proppant material is commonly known as "proppant flowback." In addition to causing increased wear on downhole and surface production equipment, the presence of particulate materials in production fluids may also lead to significant expense and production downtime associated with removing these materials from wellbores and/or production equipment. Accumulation of these materials in a well bore may also 15 restrict or even prevent fluid production. In addition, loss of proppant due to proppant flowback may also reduce conductivity of a fracture pack.

In an effort to control or prevent production of formation or proppant materials, many methods have been developed. For example, to address proppant flowback methods utilizing 20 special types of proppants and/or additives to proppants have been employed to help form a fracture pack in the reservoir which is resistant to proppant flowback. One well known method of this type utilizes resin-coated proppant materials designed to help form a consolidated and permeable fracture pack when placed in the formation. Among the ways this method may be carried out are by mixing a proppant particulate material with an epoxy resin system designed to 25 harden once the material is placed in the formation, or by the use of a pre-coated proppant material which is pumped into the formation with the fracturing fluid and then consolidated with a curing solution pumped after the proppant material is in place. Although resin-coated proppant techniques may reduce proppant flowback, they may also suffer from various problems, including incompatibility of resins with cross-linker and breaker additives in the 30 fracturing fluid, and long post-treatment shut-in times which may be economically undesirable. Resin-coated proppants may also be difficult to place uniformly within a fracture and may adversely affect fracture conductivity. In addition, resin-coated proppants are typically only

added to the final stages of fracturing treatments due to their expense, resulting in a fracture pack that is consolidated only in a region near the well bore.

Recently, techniques employing a mixture of solid proppant materials designed to achieve  
5 proppant flowback control have been developed. In one technique, rod-like fibrous materials are mixed with proppant material for the purpose of causing particle bridging within a fracture proppant pack so as to inhibit particle movement and proppant flowback. This technique is believed to control proppant flowback by forming a "mat" of fibers across openings in the pack which tends to hold the proppant in place and limit proppant flowback during fluid production.  
10 However, in practice this method has proven to have several drawbacks, including reduction in fracture conductivity at effective concentrations of fibrous materials, and an effective life of only about two years due to slight solubility of commonly used fiber materials in brine. In addition, fiber proppant material used in the technique may be incompatible with some common well-treating acids, such as hydrofluoric acid.

15

In another recently developed method, thermoplastic material in the form of ribbons or flakes is mixed with proppant material in order to form a fracture proppant pack that is resistant to proppant flowback. The thermoplastic material is designed to intertwine with proppant particles and become "very tacky" at reservoir temperatures such as those greater than about  
20 104°C (220°F). In doing so, the materials are believed to adhere to proppant material to form agglomerates that bridge against each other and help hold proppant materials in place. This method of controlling proppant flowback suffers similar drawbacks as the fiber proppant additive method described above, most notably reduced conductivity. Therefore, a method of reducing fines creation while at the same time improving fracture conductivity and reducing proppant  
25 flowback is desirable.

#### SUMMARY OF THE INVENTION

According to one aspect of the present invention there is provided a composition for fracturing a subterranean formation comprising a blend of a particulate fracture proppant material and a deformable particulate material, wherein at least a portion of individual particles  
30 of said deformable particulate material have a shape with a maximum length-based aspect ratio of equal to or less than 5 and are selected to yield upon point to point stress with particles of

said fracture proppant material under conditions of formation temperature and formation closure stress.

According to another aspect of the present invention there is provided a method of  
5 treating a subterranean formation comprising injecting a composition as described above.

Preferably the deformable particulate material has a shape that is at least one of beaded,  
cubic, bar-shaped, cylindrical, or a mixture thereof. Beaded or cylindrical shaped particulate  
materials may have a length to diameter aspect ratio of equal to or less than about 5, and  
10 bar-shaped particulate material may have a length to width aspect ratio of equal to or less than  
about 5 and a length to thickness aspect ratio of equal to or less than about 5.

Preferably the composition is a fracturing fluid composition that includes a blend of  
fracture proppant material and deformable particulate material. More preferably, the fracturing  
15 fluid composition is deposited in the subterranean formation so that the blend of fracture  
proppant material and deformable particulate material has an *in situ* conductivity greater than an  
*in situ* conductivity of either fracture proppant material or deformable particulate material alone.

Advantageously, the fracturing fluid composition is deposited in the subterranean  
20 formation so that the blend of fracture proppant material and deformable particulate material has  
an *in situ* creation of fines that is less than an *in situ* creation of fines in said fracture proppant  
material alone.

Conveniently, the deformable particulate material may have a particle size of from about  
25 4 mesh to about 100 mesh, a specific gravity of from about 0.4 to about 3.5.

BRIEF DESCRIPTION OF THE DRAWINGS

5 FIG. 1 is a representation of a uni-planar structural "mat" of fibers believed to form *in situ* using rod-like fibrous proppant additives of the prior art.

FIG. 2 is a representation of uni-planar agglomerate structures believed to form *in situ* using thermoplastic ribbon or flake proppant additives of the prior art.

10 FIG. 3 is a representation of a substantially spherical deformable beaded particle according to one embodiment of the disclosed method.

15 FIG. 4 is a representation of one mechanism believed responsible for deformation of the substantially spherical particle of FIG. 3 due to contact with fracture proppant under conditions of formation stress.

20 FIG. 5 is a representation of a multi-planar hexagonal close-packed structure believed to form *in situ* using one embodiment of the disclosed method having a 7:1 ratio of fracture proppant material to polystyrene divinylbenzene plastic beads.

FIG. 6 is a simplified representation of one possible shape of a deformable beaded particle subjected to hexagonal contact with fracture proppant material.

25 FIG. 7 is a simplified representation of one possible shape of deformable beaded particle subjected to pentagonal contact with fracture proppant material.

FIG. 8 is a simplified representation of one possible shape of a deformable beaded particle subjected to tetragonal contact with fracture proppant material.

30 FIG. 9 is a simplified representation of one possible shape of a deformable beaded particle subjected to contact in two locations by fracture proppant material.

FIG. 10 illustrates stress versus strain, and shows variation in Young's modulus of elasticity for polystyrene divinylbenzene plastic beads.

FIG. 11 illustrates volume compaction versus closure stress for polystyrene  
5 divinylbenzene plastic beads.

FIG. 12 illustrates linear compaction versus closure stress for polystyrene divinylbenzene plastic beads.

10 FIG. 13 illustrates linear compaction versus closure stress for 20/40 mesh Ottawa sand at a pack density of  $9.7 \text{ kgm}^{-2}$  ( $2 \text{ lb/ft}^2$ ).

15 FIG. 14 illustrates permeability versus closure stress for plastic beads, 20/40 mesh Ottawa sand, and 3:1 and 7:1 mixtures by volume of 20/40 plastic beads and 20/40 mesh Ottawa sand according to embodiments of the disclosed method.

FIG. 15 illustrates conductivity versus closure stress for 20/40 mesh Ottawa sand, 20/40 mesh plastic beads, and 3:1 and 7:1 mixtures by volume of 20/40 mesh Ottawa sand and 20/40 mesh plastic beads according to one embodiment of the disclosed method.

20 FIG. 16 illustrates fines generation versus closure stress for 20/40 mesh Ottawa sand and 3:1 and 7:1 mixtures of 20/40 mesh Ottawa sand and 20/40 mesh plastic beads according to embodiments of the disclosed method.

25 FIG. 17 illustrates three dimensional deformation of polystyrene divinylbenzene particles after being subjected to stress in a simulated fracture proppant pack.

FIG. 18 illustrates the flowback failure of an Ottawa sand proppant pack under a closure stress of greater than  $6.9 \times 10^6 \text{ Pa}$  (1000psi).

FIG. 19 illustrates the flowback failure of a proppant pack containing a 3:1 mixture of Ottawa sand to polystyrene divinylbenzene plastic beads under a closure stress of greater than  $6.9 \times 10^6$  Pa (1000 psi).

5 FIG. 20 illustrates the flowback failure of a proppant pack containing a 4:1 mixture of Ottawa sand to polystyrene divinylbenzene plastic beads under a closure stress of greater than  $6.9 \times 10^6$  Pa (1000 psi).

10 FIG. 21 illustrates the flowback failure of a proppant pack containing a 5.7:1 mixture of Ottawa sand to polystyrene divinylbenzene plastic beads under a closure stress of greater than  $6.9 \times 10^6$  Pa (1000 psi).

#### DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

15 In embodiments of the disclosed method, deformable particulate material (e.g., deformable particles) is added to and/or mixed with fracture proppant material to enhance conductivity and permeability of a fracture proppant pack, reduce fines generation, and/or minimize proppant flowback. By "deformable" it is meant that individual particles of a particulate material yield upon point to point stress with particles of fracture proppant material.

20 In connection with the disclosed method, the surprising discovery has been made that blends of fracture proppants and deformable particles according to embodiments of the disclosed method are synergistic in that combinations of fracture proppant material and deformable particles may possess greater conductivity and/or permeability than either material possesses alone. This synergistic effect is believed to result from a number of factors, including the *in situ* deformation of the deformable particles to form multi-planar structures or networks that, among other things, may cushion the fracture proppant material.

25

30 Surprisingly, it has also been found that combinations of deformable particles and fracture proppants according to embodiments of the disclosed method typically reduce fines generation as a result of closure stress applied on a proppant pack. In embodiments of the disclosed method, it is believed that deformable particulates act as a "cushion" to prevent grain to grain contact and absorb stress between particles of silica, synthetic or other types of proppants. It is

believed that this cushion effect prevents proppant particles from shattering or breaking due to stress (including stress induced by stress cycling) and that therefore less fines are produced. When less fines are present to lower pore space in a proppant pack, porosity, permeability and/or conductivity may be maintained. As demonstrated in Example 5 and illustrated in FIG. 16, this  
5 reduction in fines generation allows the extension of the closure stress range in which fracture proppant materials, such as sand, may be used. This means that lower cost proppants such as sand may be utilized in those applications where more expensive high strength proppants have been traditionally employed.

10 As an additional benefit, it has been found that combinations of deformable particulate and proppant material according to embodiments of the disclosed method may also reduce proppant flowback due to plastic deformation of deformable particles into multi-planar structures. In the practice of the disclosed method, deformable particles deform at formation temperatures and with proppant contact as fracture closure stress is applied. Previous methods  
15 using fracturing treatment additive materials having fiber 2 or ribbon-like (or flake) 4 geometries, are believed to address proppant flowback by creating uni-planar structures with proppant as shown in FIGS. 1 and 2. By "uni-planar" it is meant that the *in situ* structures created by these additives are believed to have geometries that extend vector stress in one plane of a proppant pack. These structures are believed to exist as individual "mats" or agglomerates within a  
20 proppant pack. Unlike the previous methods and materials, embodiments of the disclosed method are believed to result in creation of multi-planar structures (or networks) *in situ* that act to reduce or prevent proppant flowback by increasing particle cohesion and proppant pack stability. By "multi-planar" it is meant that *in situ* structures created by the treatment additives of the disclosed method are believed to have geometries that extend vector stress in more than  
25 one plane of the proppant pack, *i.e.*, in three dimensions. Therefore, structures formed in the practice of the disclosed method are believed to exist as *in situ* networks extending within, and forming part of, a fracture proppant matrix.

Particular embodiments of the disclosed method may offer further advantages. For  
30 example, when a substantially spherical deformable beaded material of the disclosed method is mixed with a relatively irregular or angular fracture proppant material such as sand, greater porosity and permeability may be achieved due to the creation of a pack geometry, such as

hexagonal packing, that is superior to the pack geometry achieved by the fracture proppant material alone. In addition, even greater fracture conductivity may be achieved using the disclosed method by blending a fracture proppant material with a deformable material having a density less than that of the fracture proppant material, resulting in a greater fracture width per  
5 unit mass.

An example of a substantially spherical deformable beaded particle 10 according to one embodiment of the disclosed method is shown in FIG. 3. FIG. 4 illustrates one possible mechanism believed responsible for deformation of a substantially spherical particle 10 of FIG. 3  
10 as a result of contact with individual particles of fracture proppant material 20 under conditions of formation stress. As seen in FIG. 4, proppant particles 20 create "dimpled" impressions 30 in the sides 40 of deformable particle 10 in which proppant particles 20 may reside.

Although a substantially spherical deformable beaded particle is illustrated in FIGS. 3 and  
15 4, it will be understood with benefit of this disclosure that non-spherical beaded particles as well as non-beaded particle shapes may also be used successfully in the practice of the disclosed method. Examples of such non-spherical beaded particles include, but are not limited to, beaded particles having a shape that is elongated in one or more dimensions, such as particles that are oval shaped, egg-shaped, tear drop shaped, or mixtures thereof. Examples of such non-beaded particles include, but are not limited to, particles having a shape that is cubic, bar-shaped (as in a hexahedron with a length greater than its width, and a width greater than its thickness), cylindrical, multi-faceted, irregular, or mixtures thereof. In addition, it will be understood with benefit of the present disclosure that beaded or non-beaded deformable particles may have a surface that is substantially roughened or irregular in nature or a surface that is substantially  
20 smooth in nature. Moreover, it will also be understood that mixtures or blends of deformable particles having differing, but suitable, shapes for use in the disclosed method may be employed.  
25

When deformable particles having a cylindrical shape or an elongated beaded shape with a substantially uniform diameter are employed in the practice of the disclosed method, particles having a length to diameter aspect ratio of equal to or less than about 5 are typically employed  
30 (as used herein, "length" is measured along the axis of a particle having the longest dimension). More typically, cylindrical or elongated beaded particles having a length to diameter aspect ratio

of equal to or less than about 3 are employed. Most typically, cylindrical or elongated beaded particles having a length to diameter aspect ratio of equal to or less than about 2 are used. Similarly, when deformable particles having a bar-shape are employed, both the length to width ratio and the length to thickness ratio of a given individual particle are typically equal to or less than about 5, more typically equal to or less than about 3, and most typically equal to or less than about 2. When deformable particles having multi-faceted or irregular shapes, or shapes with tapered diameters are employed, the particles typically have a maximum length-based aspect ratio of equal to or less than about 5, more typically equal to or less than about 3, and most typically, equal to or less than about 2. As used herein, "maximum length based aspect ratio" means the maximum aspect ratio that may be obtained by dividing the length of a particle by the minimum (or shortest) dimensional value that exists along any other axis (other than the length axis) taken through the center of mass of the particle. It will also be understood with benefit of the present disclosure that particles of any shape (including any of the shapes described in this paragraph) may be employed in the disclosed method when such particles have a maximum length-based aspect ratio that is typically equal to or less than about 5, more typically equal to or less than about 3, and most typically equal to or less than about 2.

An example of a multi-planar structure believed to form *in situ* from a mixture of deformable beaded particulate materials 10 and fracture proppant material 20 according to one embodiment of the disclosed method having a 7:1 blend of fracture proppant material to deformable particulate material is shown in FIG. 5. However, a multi-planar pack may be formed by other ratios of deformable material to fracture proppant material. When deformable particles are mixed with harder, non-deformable proppants, such as sand, proppant packs may be formed with proppant particles "locked" into deformed surfaces of the deformable particles, thus forming a stronger pack. However, no sticking or adherence between deformable particles and fracture proppant material is required in order to obtain the benefits of the disclosed method. Beaded particulate material is believed to deform into different shapes depending on the packing geometry surrounding each bead. Just a few of these shapes are illustrated in simplified geometrical form in FIGS. 6-9.

Packing geometry is believed to be dependent on factors such as irregularity of the fracture proppant material, and a variety of geometries may exist in a single fracture pack. For example, FIGS. 6-8 illustrate approximate cuboidal and pyramidal shapes of beaded particulate

material 10 that are believed to result from hexagonal (bead contacted by proppant in six locations), pentagonal (bead contacted by proppant in five locations), and tetragonal (bead contacted in four locations) packing, respectively. As shown in FIG. 9, where a bead 10 is contacted in only two locations by proppant, it may be deformed into a shape resembling a "dog bone." It will be understood with benefit of this disclosure that other packing configurations, mixtures of packing configurations, as well as numerous other shapes and mixtures of shapes of deformable particulate material are also possible.

By having appendages in several planes, stresses on a given deformable particle in one plane provides additional stabilization to adjacent particles in other planes. This effect is believed to be squared by benefit of stresses in a second plane and cubed by contributions of stresses in a third plane. In addition to contributing to beneficial effects not found in previous methods, such as increased fracture conductivity and reduced fines creation, this results in superior stabilization of a fracture pack using a lesser volume of additive material than is required in those previous methods which act in a uni-planar manner. Advantageously, this reduced volume translates into reduced material costs. In addition, the use of deformable particle embodiments of the disclosed method may allow a well to be put on production faster than resin coated sand methods which require shut-in time for resin curing, thus providing a more rapid return on investment.

20

Advantageously, embodiments of the disclosed method may be selected to be chemically compatible with fracture fluid additives. In the practice of the disclosed method, deformable particles may be mixed with any substantially non-deformable proppant suitable to maintain a fracture in an oil, gas, geothermal, coalbed methane, water or other subterranean well. Such substantially non-deformable fracture proppant materials include, for example, silica (such as Ottawa, Brady or Colorado Sands), synthetic organic particles, glass microspheres, ceramics (including aluminosilicates such as "CARBOLITE (RTM)," "NAPLITE" or "ECONOPROP"), resin-coated sand (such as "ACME BORDEN (RTM) PR 6000" or "SANTROL (RTM) TEMPERED HS"), sintered bauxite, and mixtures thereof. Typically, sand or synthetic fracture proppants are used. Most typically, sand is used as a fracture proppant.

In the practice of the disclosed method, any natural or synthetic particulate material that is substantially deformable under reservoir conditions in the presence of fracture proppant material to prevent formation of fines, improve fracture conductivity, and/or reduce flowback of proppant or formation materials may be employed. Examples of such substantially deformable particulate materials include, but are not limited to, those deformable materials having a Young's modulus of between about  $3.4 \times 10^6$  Pa (500 psi) and about  $3.4 \times 10^9$  Pa (500,000 psi) at formation conditions, more typically between about  $34 \times 10^6$  Pa (5,000 psi) and  $1.4 \times 10^9$  Pa (200,000 psi) at formation conditions, and most typically between about  $48 \times 10^6$  Pa (7,000) and  $1.0 \times 10^9$  Pa (150,000) at formation conditions. When used in the disclosed method, substantially deformable materials should also have a glass transition temperature that is greater than the reservoir temperature.

Depending on formation conditions, materials that may be suitable in the practice of the disclosed method may include, but are not limited to cellulose acetate butyral, polystyrene acrylonitrile, polytetrafluoroethylene, diglycol allyl carbonates, epoxy resins, polyester, furan, phenol formaldehyde, phenolic epoxy, urea aldehydes, silicones, acrylics, vinyl acetates, casein, and natural and synthetic rubbers. For example, at formation temperatures of from about 10°C (50°F) to about 232°C (450°), crosslinked elastomeric or polymeric materials are typically employed.

20

Polymers that may be crosslinked for purpose of the disclosed method may include, but are not limited to, polystyrene, methylmethacrylate, nylon, polycarbonates, polyethylene, polypropylene, polyvinylchloride, polyacrylonitrile-butadiene-styrene, polyurethane, or any other suitable polymer, and mixtures thereof. For example, suitable crosslinkers may include divinylbenzene. Particularly suitable materials may include deformable particles manufactured of resin and/or those commercially available materials that do not substantially interact chemically with components of well treatment fluids and which are stable in a subterranean formation environment.

30

In the practice of the disclosed method deformable particles of crosslinked polymers may contain varying percentages of crosslinkers to produce proppant packs having varying stabilities and conductivities. In this regard, any amount of crosslinker suitable for forming a deformable

particle may be employed. Percentages of crosslinker employed may be selected on many factors if so desired, such as the intended use of the deformable particle, the specific crosslinking agent, and other constituents which may optionally be present in the deformable particles. For example, changing the percentage of divinylbenzene crosslinker present in polystyrene divinylbenzene beads from about 4% to about 0.5% to about 0.3% changes the confined Young's modulus at standard conditions from about  $4.8 \times 10^8$  Pa (70,000 psi) to about  $3.4 \times 10^8$  (50,000 psi) to about  $2.1 \times 10^8$  Pa (30,000 psi), respectively.

In one embodiment of the disclosed method employing polystyrene divinylbenzene beads, polystyrene divinylbenzene plastic beads typically having less than 10%, more typically less than about 5%, even more typically less than about 4%, even more typically less than about 3%, even more typically less than about 2%, even more typically less than about 1%, and even more typically less than about 0.5%, and most typically less than or equal to about 0.3% by weight of divinylbenzene crosslinker are employed. However, it will be understood with the benefit of the present disclosure that polystyrene divinylbenzene beads having amounts of divinylbenzene crosslinker greater than about 10% by weight and less than about 0.2% or less than about 0.1% by weight may also be employed. In another embodiment, crosslinked polymers for use in the disclosed method may include polystyrene divinylbenzene plastic beads containing typically from about 0.1% to about 10%, more typically from about 0.2% to about 4%, even more typically from about 0.3% to about 4%, even more typically from about 0.5% to about 4%, even more typically from about 0.3% to about 2%, even more typically from about 0.3% to about 1%, and most typically from about 0.3% to about 0.5% divinylbenzene crosslinker by weight. In still other separate embodiments, polystyrene divinylbenzene plastic beads containing respective amounts of about 0.3%, about 0.4%, about 0.5% to about 4%, or about 4% by weight divinylbenzene crosslinker may be employed.

It will be understood with benefit of the present disclosure that polystyrene divinylbenzene plastic beads having the above-described ranges of divinylbenzene crosslinker may be used under a wide variety of formation conditions. For example, it may be preferable to use beads containing less divinylbenzene crosslinker at lower formation closure stresses. Thus, in one embodiment, polystyrene divinylbenzene plastic beads having from about 0.3% to about 0.5% by weight divinylbenzene crosslinker may optionally be employed in the treatment of

formations having closure stresses of less than about  $41 \times 10^6$  Pa (6000psi). In another embodiment, polystyrene divinylbenzene plastic beads having greater than or equal to about 4% by weight divinylbenzene crosslinker may optionally be employed in treatment formations having closure stresses of greater than about  $41 \times 10^6$  Pa (6000). It will be understood with benefit of 5 this disclosure that these specific examples only serve to illustrate certain typical embodiments and therefore do not limit the use of the various polystyrene divinylbenzene beads having these or other specific percentages of divinylbenzene crosslinker at other closure stresses or ranges of closure stresses than so exemplified.

10 For illustration purposes, Table I includes a partial listing of melting point, glass transition temperature and Young's modulus of elasticity values for some of the polymer materials listed above. In the practice of the disclosed method, polystyrene divinylbenzene particles are typically employed at formation temperatures from about 66°C (150°F) to about 149°C (300°F), and at formation stress values of from about  $3.4 \times 10^6$  Pa (500 psi) to about 8.2  
15  $\times 10^6$  Pa (1200 psi). For lower formation temperatures, such as below about 66°C (150°F), materials such as rubbers or non-crosslinked polymers, including non-crosslinked species of those polymers described above, may be suitable. At higher formation temperatures, such as above about 149°C (300°F), materials such as polyvinylchloride or metals, preferably soft metals, including lead, copper, and aluminum, may be employed. For any given material, values of  
20 Young's modulus may vary with *in situ* formation conditions, such as temperature and pressure (or stress). As an example, FIG. 10 illustrates the relationship between values of Young's modulus and stress for polystyrene divinylbenzene beads.

TABLE I

Polymer	Melting Point, °C	Glass Transition Temp, °C	Modulus of Elasticity, Pa	
			Lower Range	Upper Range
polyacrylonitrile-butadiene-styrene		90-120	---	
melamine-formaldehyde			$9.0 \times 10^9$ (1,300,00)	$1.34 \times 10^{10}$ (1,950,00)
polystyrene	240	85-105	$2.8 \times 10^8$ (400,000)	$4.1 \times 10^9$ (600,000)
methylmethacrylate	100		$2.4 \times 10^9$ (350,000)	$3.4 \times 10^9$ (500,000)
polycarbonate		105	$2.0 \times 10^9$ (290,000)	$2.24 \times 10^9$ (325,000)
polyvinylchloride	285	75-105	$1.4 \times 10^9$ (200,000)	$4.1 \times 10^9$ (600,000)
high density polyethylene	135		$5.9 \times 10^8$ (85,000)	$1.1 \times 10^9$ (160,000)
low density polyethylene	115		$2.4 \times 10^8$ (35,000)	$6.2 \times 10^8$ (90,000)
polystyrene divinylbenzene			$4.8 \times 10^6$ (7,000)	$1.0 \times 10^9$ (150,000)
polypropylene	168	25	$9.6 \times 10^6$ (1,400)	$11.7 \times 10^6$ (1,700)
polyurethane		90-105		

FIG. 5 illustrates just one embodiment of a multi-planar structure believed to be formed *in situ* between beaded deformable particles and fracture proppant material in the practice of the disclosed method. In the disclosed method, deformable particles of any size and shape suitable for forming multi-planar structures or networks *in situ* with fracture proppants may be employed, such as those particles having shapes as mentioned previously. This also includes any deformable particles suitable for forming multi-planar structures or networks that offer improved fracture conductivity and/or reduced fines creation over conventional proppant packs.

10

It is believed that the optimal size of deformable particulate material relative to fracture proppant material may depend, among other things, on *in situ* closure stress. For example, a deformable particulate material having a larger size than the fracture proppant material may be desirable at a closure stress of about  $6.9 \times 10^6$  Pa (1000 psi) or less, while a deformable particulate material equal in size to the fracture proppant material may be desirable at a closure stress of about  $3.4 \times 10^6$  Pa (5000 psi) or greater. Although deformable particulate material smaller than the fractured proppant may be employed, in some cases it may tend to become wedged or lodged in the fracture pack

interstitial spaces. Typically, deformable particles used in the disclosed method typically have a beaded shape and a size of from about 4 mesh to about 100 mesh, more typically from about 16 mesh to about 40 mesh, and most typically about 20/40 mesh. Thus, in one embodiment, deformable particles may range in size from about 1 or 2 mm to about 0.1 mm; more typically their size will be from about 0.2 mm to about 0.8 mm, more typically from about 0.4 mm to about 0.6 mm, and most typically about 0.6 mm. However, sizes greater than about 2 mm and less than about 0.1 mm are possible as well.

Non-deformable fracture particles having a size substantially equivalent or marginally larger than a selected fracture proppant size are typically employed. Fracture proppant sizes may be any size suitable for use in a fracturing treatment of a subterranean formation. Typically, in the disclosed method fracture proppant sizes range from about 4 mesh to about 100 mesh, more typically from about 12 mesh to about 50 mesh, and most typically about 20/40 mesh.

Deformable particles having any density suitable for fracturing a subterranean formation may be employed in the practice of the disclosed method. However, in one typical embodiment, the specific gravity of a deformable particulate material is from about 0.3 to about 3.5, more typically from 0.4 to about 3.5, more typically from about 0.5 to about 3.5, more typically from about 0.6 to about 3.5, and even more typically from about 0.8 to about 3.5. More typically a deformable particulate material having a specific gravity of from about 1.0 to about 1.8 is employed, and most typically a deformable particle having a specific gravity of about 1.0 to about 1.1 is employed. In another specific embodiment, a particular divinylbenzene crosslinked polystyrene particle may have a specific gravity of from about 0.4 to about 0.65, and most typically of about 0.6. However, other specific gravities are possible. Advantageously, when deformable particles having a density less than that of a selected fracture proppant material are employed, reduced treating pressures and concentration levels of potentially formation-damaging gelled or viscous fluids may be employed. This may allow higher treating rates and/or result in higher formation productivity.

Deformable particles may be mixed and pumped with fracture proppant material throughout or during any portion of a hydraulic fracturing treatment in the practice of the disclosed method. However, when deformable particulate material is mixed with only a portion

of a fracture proppant material pumped into a formation, it is typically mixed with proppant during the latter stages of the treatment in order to dispose the deformable particulate material in the fracture pack at or near the point where the well bore penetrates a subterranean formation. In the practice of the disclosed method, it is also possible that mixtures of deformable particles 5 and fracture proppant material may be pumped in any number of multiple stages throughout a fracture treatment job.

In the practice of the disclosed method, any suitable concentration of deformable particles may be mixed with fracture proppant material, with greater concentrations of 10 deformable particles typically resulting in a greater reduction in fines generation for a given formation and proppant material. Typically, a ratio of fracture proppant to deformable particulate material may be from about 1:1 to about 15:1 by volume. More typically, a ratio of fracture proppant to deformable particulate material is about 3:1 to about 7:1. Most typically, a ratio of about 3:1 is employed.

15       In the practice of the disclosed method, deformable particulate material may be mixed with a fracture proppant or mixture of fracture proppants in any manner suitable for delivering such a mixture to a subterranean formation. For example, deformable particles may be mixed with a fracture proppant prior to mixing with carrier fluid, or deformable particles may be mixed 20 with carrier fluid before or after a carrier fluid is mixed with a proppant. Deformable particulate materials may also be mixed in a solution which is later added to proppant or carrier fluid as it is pumped. Additionally, mixtures or blends of deformable particles and fracture proppant may be injected into a subterranean formation in conjunction with other treatments at pressures sufficiently high enough to cause the formation or enlargement of fractures, or to otherwise 25 expose the blend of deformable particles and fracture proppant material to formation closure stress. Such other treatments may be near wellbore in nature (affecting near wellbore regions) and may be directed toward improving wellbore productivity and/or controlling the production of fracture proppant or formation sand. Particular examples include gravel packing and "frac-packs."

30

In the practice of the disclosed method, any carrier fluid suitable for transporting a mixture of fracture proppant material and deformable particles into a formation fracture in a

subterranean well may be employed including, but not limited to, carrier fluids comprising salt water, fresh water, liquid hydrocarbons, and/or nitrogen or other gases. Suitable carrier fluids include or may be used in combination with fluids have gelling agents, cross-linking agents, gel breakers, curable resins, hardening agents, solvents, surfactants, foaming agents, demulsifiers, buffers, clay stabilizers, acids, or mixtures thereof.

The polystyrene divinylbenzene plastic beads for use with the disclosed methods may be prepared by methods that would be apparent to those of skill in the art or purchased from "DOW CHEMICAL."

10

Typically, cross-linked polystyrene beads having a specific gravity of from about 1.0 to about 1.8 are employed. In a most typical embodiment of the disclosed method, 20-40 mesh polystyrene divinylbenzene copolymer plastic beads having a specific gravity of about 1.0 are mixed with 20/40 mesh Ottawa sand at a ratio of about 3:1 by weight. These beads are commercially available as a lubrication fluid from "SUN DRILLING PRODUCTS" under the brand name "LUBRAGLIDE (RTM)," or as ion exchange beads manufactured by "DOW CHEMICAL." These beads offer crush resistance, are resistant to solvents, and are substantially round and smooth, having length to width and length to height ratios of about 1:1. Since the polystyrene divinylbenzene plastic beads of this embodiment have a reduced bulk density (*i.e.*, about  $0.64 \text{ gm/cm}^3$ ), the beads may be suspended in frac fluids with a significant reduction in gelling agents. With a reduction in density, these plastic beads require less packing density (*i.e.*,  $\text{gm}^{-2}$ ) to achieve the same fracture width. Test results indicated that these plastic beads are deformable under conditions of stress and relative to sand proppant. Test results also showed that these beads are compatible with oil field solvents and acids. Favorable formation treating characteristics offered by polystyrene divinylbenzene beads include, among other things, strength, crush resistance, chemical resistance, elasticity, high glass transition temperature. These beads are also "non-creeping" (*i.e.*, resistant to slow change in shape due to constant force):

30

When plastic beads of this embodiment are mixed with substantially spherical fracture proppant material of substantially uniform size, a hexagonal-close-pack (HCP) structure is believed to be possible (*i.e.*, typically generating six contact points for each plastic bead). Each

contact point may generate a substantially flat face at higher stresses as the plastic grains are forced into a smaller volume, such as under conditions of closure stress. Since plastic beads of this embodiment of the disclosed method may deform to form substantially flat surfaces on multiple sides, Young's modulus for a proppant pack incorporating these beads may be increased, consequently increasing particle cohesion and proppant pack stability, and decreasing flowback of proppant. When plastic beads of this embodiment are mixed with harder, non-deformable proppants, such as sand, proppant packs may be formed with proppant particles "locked" into deformed surfaces of the plastic beads, thus forming a stronger pack. Although substantially spherical fracture proppant material of substantially uniform size is described in this embodiment, it will be recognized with benefit of this disclosure that non-spherical and/or non-uniformly sized fracture proppant material may also be successfully employed in the practice of the disclosed method.

### EXAMPLES

15

The following examples are illustrative and should not be construed as limiting the scope of the invention or claims thereof.

#### Examples 1-3: Plastic Beads

20

Polystyrene divinylbenzene copolymer plastic beads with a 20/40 mesh size were tested alone (without other proppant materials) using modified API standards. These beads contained about 4% divinylbenzene by weight. These plastic beads used in this example were found to pass the standard API RP 56 test for roundness, sphericity, and acid solubility (*i.e.*, 0.5%).

25

Testing was also performed to determine if any swelling in solvents occurred. The beads were placed in xylene at room temperature and photographed over 65 hours. No swelling occurred under these conditions. Standard API crush testing was also performed on the beads at stresses between  $14 \times 10^6$  and  $55 \times 10^6$  Pa (2000 and 8000 psi). It was found that plastic beads of this type typically do not fracture or shatter in a brittle manner to generate fines under stress, but instead "plastically" deform to form flat dimples on the round surface. Consequently, non-API tests were performed to determine the crush properties of the beads.

Example 1: API RP 56 Evaluation

The polystyrene divinylbenzene plastic beads of this embodiment had a sphericity of 0.9 and roundness of 0.9 which is suitable for proppant use since it meets the required minimum value of 0.6 for each property. A sieve analysis of the material contained an acceptable 93.8% 5 20/40 distribution with 6.1% retained on the 50 mesh screen and 0.1% fines. The acid solubility at 150°F was an acceptable 0.5% using a 12-3 HCl-HF acid.

Example 2: API Crush Testing

To measure propensity of polystyrene divinylbenzene plastic beads of this embodiment to 10 generate fines under closure stress, the plastic beads were crush tested at confining stresses of  $14 \times 10^6$ ,  $28 \times 10^6$ ,  $41 \times 10^6$  and  $5.5 \times 10^6$  Pa (2000, 4000, 6000 and 8000 psi) using Equation 7.1 in API RP 60. An initial starting mass of 15.71 gm for a measured bulk density of 0.636 gm/cm<sup>3</sup> using a 5.1cm (2 inch) diameter crush cell was calculated. The results of the crush test are given in Table II where the weight percent of fines are given for an initial 6.2% "fines" 15 distribution material at zero stress. The third column estimates the fines less than 50 mesh by subtracting the initial 6.1% 50 mesh particles.

**TABLE II**  
**Weight Per Cent Fines for Plastic Bead Crush Tests**

Crush Stress (Pa (psi))	Fines (wt %)	Fines (Less Than 50 Mesh) (wt%)
0	6.2	0.1
$14 \times 10^6$ (2000)	6.9	0.7
$28 \times 10^6$ (4000)	6.9	0.7
$55 \times 10^6$ (8000)	5.0	*

The results given in Table II indicate that the plastic particles are "crush resistant" since the percentage of fines are less than 14% at all stress levels.

25 Example 3: Non-API Crush Testing

To measure deformation properties of the polystyrene divinylbenzene beads of this embodiment, the plastic bead material was slowly (*i.e.*, 2 minutes) stressed in a 2.5cm (1 inch)

diameter cell by computer control of the measured load while accurately monitoring the change in sample volume by using a sensitive linear variable differential transducer (LVDT) calibrated to 0.001 inch accuracy.

5 In FIG. 11, volume per cent change in plastic beads is plotted as a function of closure stress. At  $14 \times 10^6$  Pa (2000 psi) closure stress, 25% of the bulk bead volume has been lost due to pore volume changes. At  $41 \times 10^6$  Pa (6000 psi) closure stress, essentially all of the pore volume is lost (*i.e.*, 42%) due to compaction, and the beads are essentially a conglomerate solid. This large compaction of plastic beads is shown in FIG. 12 where the change in fracture width is  
10 plotted versus stress. The change in fracture width is measured in the English unit mils (*i.e.*, 1 mil = 0.001 inches). For comparison, the same measurements are shown in FIG. 13 for 20/40 mesh Ottawa sand proppant at  $9.8\text{kgm}^{-2}$  (2 lb/ft<sup>2</sup>). At  $28 \times 10^6$  Pa (4000 psi) closure stress, the plastic beads are compacted 5.3mm (210 mils). Ottawa sand is compacted only 0.43mm (17 mils). The data in FIGS. 12 and 13 indicate that the compaction of plastic beads are a factor of  
15 12 times larger than the compaction of Ottawa sand. For Ottawa sand, proppant crushing starts at about  $31 \times 10^6$  Pa (4500 psi) and increases significantly for stress greater than  $41 \times 10^6$  Pa (6000 psi).

#### Examples 4-6: Plastic Bead/Ottawa Sand Mixtures

20 Conductivity analyses were performed on combinations of plastic beads and Ottawa sand at 93°C (200°F). Results of these analyses are presented in Tables III and IV, and graphically in FIGS. 14 and 15.

25 Example 4: Conductivity Testing

Conductivity tests were performed on a combination of 20/40 mesh polystyrene divinylbenzene plastic beads and combinations of 20/40 mesh Ottawa sand and 20/40 mesh polystyrene divinylbenzene plastic beads according to the present embodiment. Tests were performed using a "DAKE" hydraulic press having a "ROSEMOUNT" differential transducer  
30 (#3051C) and controlled by a "CAMILE" controller. Also employed in the testing was a "CONSTAMETRIC 3200" constant rate pump. In addition to testing 20/40 plastic beads alone, a 7:1 mixture of  $8.54\text{kgm}^{-2}$  (1.75 lbs/ft<sup>2</sup>) of 20/40 mesh Ottawa sand to  $1.22\text{kgm}^{-2}$  (0.25 lbs/ft<sup>2</sup>)

of 20/40 mesh plastic beads, and a 3:1 mixture of  $7.32 \text{kgm}^{-2}$  (1.50lbs/ft<sup>2</sup>) of 20/40 mesh Ottawa sand to  $2.44 \text{kgm}^{-2}$  (0.50lbs/ft<sup>2</sup>) of 20/40 mesh plastic beads were also tested. Averaged test results are given in Tables III and IV, as well as FIGS. 14 and 15. For comparison purposes, conductivity and permeability data for 20/40 Ottawa sand published by "STIMLAB" is also presented.

As shown in Tables III and IV, test results indicate that combinations of plastic beads and Ottawa sand according to this embodiment of the disclosed method may have a positive synergistic effect on permeability and conductivity.

10

TABLE III  
Permeability at Varying Closure Stresses

Closure Stress (Pa (psi))	Permeability, Darcies			
	20/40 Mesh Ottawa Sand	20/40 Mesh Plastic Beads	3:1 Combination	7:1 Combination
$6.9 \times 10^6$ (1000)	277	235	356	
$14 \times 10^6$ (2000)	248	99	272	262
$28 \times 10^6$ (4000)	142		189	143
$41 \times 10^6$ (6000)	45		120	52
$55 \times 10^6$ (8000)	16		55	17
$69 \times 10^6$ (1000)	9		36	

TABLE IV  
Conductivity at Varying Closure Stresses

Closure Stress (Pa (psi))	Conductivity, md-m (md-ft)			
	20/40 Mesh Ottawa Sand	20/40 Mesh Plastic Beads	3:1 Combination	7:1 Combination
$6.9 \times 10^6$ (1000)	1565 (5135)	2167 (7110)	2547 (8355)	
$14 \times 10^6$ (2000)	1323 (4340)	994 (3260)	1761 (5778)	1653 (5424)
$28 \times 10^6$ (4000)	805 (2640)		918 (3013)	857 (2811)
$41 \times 10^6$ (6000)	359 (1178)		399 (1310)	298 (977)
$55 \times 10^6$ (8000)	89 (292)		297 (976)	90 (295)
$69 \times 10^6$ (10000)	50 (164)		195 (639)	

As shown in Table III and FIG. 14, at a 3:1 mixture of  $7.3\text{kgm}^{-2}$  ( $1.50\text{lbs}/\text{ft}^2$ ) of 20/40 mesh Ottawa sand to  $2.4\text{kgm}^{-2}$  ( $0.50\text{ lbs}/\text{ft}^2$ ) of plastic beads there was a consistent increase in permeability over 20/40 Ottawa proppant alone. At  $14 \times 10^6$  Pa (2000 psi) closure the increase in mixture permeability over Ottawa sand was approximately 10% (from about 250 darcy to about 270 darcy), at  $28 \times 10^6$  Pa (4000 psi) the increase was approximately 35% (from about 140 darcy to about 190 darcy), and at  $55 \times 10^6$  Pa (8000 psi), the increase was approximately 240% (from about 16 darcy to about 55 darcy). Significantly, at  $69 \times 10^6$  Pa (10,000 psi) closure stress, the about 36 darcy permeability of the 3:1 combination is approximately 300% greater than the about 9 darcies permeability of Ottawa sand alone. Among other things, this test demonstrated the ability of the beads to reduce the production of fines by Ottawa at higher closures stresses by preventing grain to grain contact between grains of proppant.

15

It may also be seen in Table III and FIG. 14 that at  $93^\circ\text{C}$  ( $200^\circ\text{F}$ ) a 7:1 mixture of  $8.54\text{kgm}^{-2}$  ( $1.75\text{ lbs}/\text{ft}^2$ ) 20/40 mesh Ottawa sand to  $1.22\text{kgm}^{-2}$  ( $0.25\text{ lbs}/\text{ft}^2$ ) plastic beads yields permeability values closer to those of Ottawa sand alone than does a 3:1 mixture. However, Table IV and FIG. 14 show that the 7:1 mixture yielded increased conductivity values over Ottawa sand for all but the  $41 \times 10^6$  Pa (6000 psi) test closure stress. Furthermore, for temperatures below  $93^\circ\text{C}$  ( $200^\circ\text{F}$ ), greater permeability and conductivity improvements may be expected with a 7:1 mixture. It will also be understood with benefit of the present disclosure that mixtures of deformable particulate material and fracture proppant according to the disclosed

method may be used to successfully reduce fines generation and/or proppant flowback independent of, or without, any associated permeability or conductivity improvement over fracture proppant alone.

5 Referring again to FIG. 11, deformation tests demonstrated that a deformable particulate, in this embodiment a polystyrene divinylbenzene bead of 20/40 U.S. Mesh size and containing about 4% divinylbenzene by weight, deforms to consume approximately 33% of the existing pore space at  $6.9 \times 10^6$  Pa (1000 psi) closure stress. At  $14 \times 10^6$  Pa (2000 psi) closure approximately 55% deformation had occurred and at  $55 \times 10^6$  Pa (8000 psi) the pore space was  
10 essentially nil. However, as shown in FIG. 15, when 20/40 mesh polystyrene divinylbenzene beads of this embodiment are combined with 20/40 mesh Ottawa fracturing sand in a 3:1 ratio by volume, conductivity at all stress values listed above is greater than either proppant alone. At  $6.9 \times 10^6$  Pa (1000 psi) closure stress the 3:1 mixture had a conductivity of approximately 2547 md-m (8355 md-ft) while the conductivity of 20/40 mesh Ottawa proppant alone is 1565  
15 md-m (5135 md-ft) and conductivity of polystyrene divinylbenzene beads alone was found to be 2167 md-m (7110 md-ft). At  $14 \times 10^6$  Pa (2000 psi) closure stress the conductivity values are 1761 md-m (5778 md-ft) for the 3:1 mixture, 1323 md-m (4340 md-ft) for the 20/40 mesh Ottawa sand, and 994 md-m (3260 md-ft) for the plastic beads. At  $41 \times 10^6$  Pa (6000 psi) the 3:1  
20 mixture gave 399 md-m (1310 md-ft) while 20/40 mesh Ottawa sand alone has a conductivity of 359 md-m (1178 md-ft). In FIG. 15, a similar effect may be observed for the 7:1 mixture.

#### Example 5: Crush Testing

Reduction in fines generation using embodiments of the disclosed method is evidenced in crush tests performed on 3:1 and 7:1 by volume mixtures of 20/40 mesh Ottawa sand and the  
25 polystyrene divinylbenzene beads of the present embodiment. As shown in FIG. 16, the fines generated as a percentage of proppant (20/40 mesh Ottawa) decreases with increasing concentration of deformable plastic material. For example, at  $41 \times 10^6$  Pa (6000 psi) closure stress, 22% fines were generated by 20/40 mesh Ottawa sand above. This level of fines generation is above the API recommended maximum fines generation of 20% for proppant applications. For a 7:1 ratio of 20/40 mesh Ottawa sand to 20/40 mesh polystyrene  
30 divinylbenzene beads, approximately 13% fines were generated. For a 3:1 ratio of 20/40 mesh Ottawa sand to 20/40 mesh polystyrene divinylbenzene beads (4% divinylbenzene) only about

8% fines were generated. These levels of fines generation are well below the API recommended maximum.

As seen in FIG. 16, percentage reduction in fines for 20/40 mesh Ottawa sand/20/40 mesh polystyrene divinylbenzene bead mixtures was even greater at higher closure stresses. For example, at  $55 \times 10^6$  Pa (8000 psi) closure stress, approximately 33% fines were generated for 20/40 mesh Ottawa sand alone, 22% fines for a 7:1 mixture and 13% fines for a 3:1 mixture. At  $69 \times 10^6$  Pa (10,000 psi) closure stress, 40% fines were produced for 20/40 mesh Ottawa sand, 29% for a 7:1 mixture and 15% for a 3:1 mixture. Significantly, the level of fines generation for the 3:1 mixture remained 20%, even at  $69 \times 10^6$  Pa (10,000 psi) closure stress.

These test results indicate that the fines reduction advantages of the disclosed method may be realized under a wide variety of closure stress conditions. These results also demonstrate that the useable range of fracture proppant materials, such as Ottawa sand, may be extended to higher stress levels using deformable particles of the disclosed method.

#### Example 6: Packing Geometries

Referring to FIG. 17, photographs of polystyrene divinylbenzene beads obtained from a stereo microscope are shown. These beads were mixed with an Ottawa sand fracture proppant at a ratio of 3:1 to form a simulated proppant pack, and then subjected to a stress of  $69 \times 10^6$  Pa (10,000 psi). Stress was then relieved and the deformed polystyrene divinylbenzene beads photographed. As shown in FIG. 17, three dimensional structures were formed under stress between deformable polystyrene divinylbenzene beads 110 and 120 and fracture proppant particles 116, leaving dimpled surfaces 114 and 124 on sides of beads 110 and 120, respectively, without sticking or adherence of the beads 110 and 120 to the fracture proppant particles 116. The results of this example indicate that embodiments of the disclosed method achieve three dimensional multi-planar structures when subjected to formation stress.

#### Example 7: Flowback Tests

Proppant flowback failure was determined for Ottawa sand and mixtures of Ottawa sand to polystyrene divinylbenzene beads ranging from about 3:1 to about 6:1. For comparison purposes, proppant flowback failure was also determined for Ottawa sand alone. The

polystyrene divinylbenzene beads employed for these tests contained about 0.5% divinylbenzene crosslinker by weight, had a Young's confined modulus of about  $3.4 \times 10^8$  Pa (50,000 psi), and had a size of about 40 mesh.

5       The proppant samples were loaded into a standard conductivity cell at  $9.8 \text{ kgm}^{-2}$  ( $2 \text{ lbs}/\text{ft}^2$ ). The width of the pack was measured throughout the test using an LVDT. The differential pressure between the input and output flow of water through the pack was measured employing a Rosemount PD transducer and the rate of the flow was measured by a Micromotion D6 mass flow meter. Closure stress (approximately  $6.9 \times 10^6$  Pa (1000 psi)) was applied to the  
10      pack. The end of the conductivity cell was then removed to expose the proppant pack and replaced with a lexan tube filled with water. This allowed sand to flow into the tube at failure. Water was then pumped through the pack at flow rates increasing incrementally by 10 ml/minute intervals until pack failure which was judged by width of the pack and the loss of differential pressure. The temperature of the water flowing into the pack and the cell were maintained at  
15      between about  $6.9 \times 10^6$  Pa.

As can be seen from FIGS. 18-21, compositions of Ottawa sand/polystyrene divinylbenzene bead mixtures (FIGS. 19-21) failed at flow rates of greater than approximately 110 ml/min while the Ottawa sand composition failed at flow rates of from about 60 to 80  
20      ml/min. Thus, the present invention allows for a significant improvement (approximately 150%) in the stability of the pack while still improving the conductivity at a closure stress of about  $6.9 \times 10^6$  Pa (1000 psi).

Claims:

1. A composition for fracturing a subterranean formation comprising a blend of a particulate fracture proppant material and a deformable particulate material, wherein at least a portion of individual particles of said deformable particulate material have a shape with a maximum length-based aspect ratio of equal to or less than 5 and are selected to yield upon point to point stress with particles of said fracture proppant material under conditions of formation temperature and formation closure stress.
2. The composition of claim 1, wherein said deformable particulate material has a Young's modulus of between  $3.4 \times 10^6$  Pa and  $3.4 \times 10^9$  Pa (500 psi and 500,000 psi) at *in situ* formation conditions.
3. The composition of claim 1 or 2, wherein said deformable particulate material comprises at least one of a polymer, a crosslinked polymer, a metal, or a mixture thereof.
4. The composition of claim 3, wherein said deformable particulate material comprises polystyrene divinylbenzene.
5. The composition of claim 4, wherein the polystyrene divinylbenzene comprises from 0.3% to 4% divinylbenzene by weight.
6. The composition of claim 5, wherein the polystyrene divinylbenzene comprises from 0.5% to 4% divinylbenzene by weight.
7. The composition of claim 5, wherein the polystyrene divinylbenzene comprises from 0.3% to 0.5% divinylbenzene by weight.

8. The composition of any preceding claim, wherein said deformable particulate material comprises individual particles having a shape that is at least one of beaded, cubic, bar-shaped, cylindrical, multi-faceted, irregular, tapered, or a mixture.

9. The composition of any preceding claim, wherein said fracture proppant material comprises at least one of silica, resin-coated sand, ceramic particles, synthetic organic particles, glass microspheres, sintered bauxite, or a mixture thereof.

10. The composition of any preceding claim, wherein said fracture proppant material comprises sand, and wherein said deformable beaded material comprises polystyrene divinylbenzene.

11. The composition of claim 10, wherein said fracture proppant material has a particle size of from 4 mesh to 100 mesh, and wherein said deformable particulate material has a particle size of from 4 mesh to 100 mesh.

12. The composition of Claim 8;

wherein each of said beaded and cylindrical shaped particulate materials has a length and a diameter, wherein each of said bar-shaped particulate materials has a length, a width, and a thickness, and wherein each of said multi-faceted, irregular, and tapered particulate materials has a length; and

wherein said beaded shaped particulate materials have a length to diameter aspect ratio of equal to or less than 5, wherein said cylindrical shaped particulate materials have a length to diameter aspect ratio of equal to or less than 5, wherein said multi-faceted, irregular, and tapered particulate materials have a maximum length-based aspect ratio of equal to or less than 5, and wherein said bar-shaped particulate material has a length to width aspect ratio of equal to or less

than 5 and a length to thickness aspect ratio of equal to or less than 5.

13. The composition of any preceding claim, wherein a ratio of said fracture proppant material to said deformable particulate material in said blend is from 1:1 to 15: 1 by volume.

14. The composition of any preceding claim, wherein said deformable particulate material has a specific gravity of from 0.4 to 3.5.

15. The composition of any preceding claim, wherein said deformable particulate material comprises individual particles having a shape that is beaded.

16. The composition of any preceding claim wherein said deformable particulate material comprises individual particles having a shape that is substantially spherical.

17. The composition of any preceding claim, wherein said deformable particulate material comprises individual particles having a particle size of 20/40 mesh, a specific gravity of from 1.0 to 2.0, and a beaded particle shape.

18. The composition of any preceding claim wherein the individual particles of said deformable particulate material have a particle size of from 4 mesh to 100 mesh, and a specific gravity of from 0.4 to 3.5.

19. The composition of any one of the preceding claims wherein said deformable particulate material comprises at least one of a polymer, a crosslinked polymer, a metal, or a mixture thereof, and wherein said fracture proppant material comprises at least one of silica, resin-coated sand, ceramic particles, synthetic organic particles, glass microspheres, sintered bauxite, or a mixture thereof

20. The composition of claim 19, wherein said fracture proppant material has a particle size of from 4 mesh to 100 mesh, and wherein the ratio of said fracture proppant material to said deformable particulate material is from 1:1 to 15: 1 by volume.

21. The composition of claim 20, wherein said fracture proppant material comprises sand, wherein said deformable particulate material comprises polystyrene divinylbenzene, and wherein said deformable particular material comprises individual particles having a beaded shape.

22. A method of treating a subterranean formation, comprising:

injecting a composition comprising a blend of fracture proppant material and deformable particulate material according to any preceding claim into said subterranean formation.

23. The method of claim 22, wherein said injecting comprises injecting said blend into said subterranean formation at a pressure above a fracturing pressure of said subterranean formation.

24. The method of claim 22 or 23 wherein said injecting comprises injecting said blend into said subterranean formation and depositing said blend in a near wellbore region.

25. The method of any one of claims 22 to 23 wherein said deformable particulate material is present within said blend in an amount effective so that at said formation conditions of temperature and closure stress, an *in situ* conductivity of said blend of fracture proppant material and deformable particulate material is greater than an *in situ* conductivity of either one of said fracture proppant material or deformable particulate material alone.

26. The method of any one of Claims 22 to 25, wherein said deformable particulate material is present within said blend in an amount effective so that at said formation conditions of temperature and closure stress, an *in situ* creation of fines in said blend of fracture proppant

material and deformable particulate material is less than an *in situ* creation of fines in said fracture proppant material alone.

27. The method of any one of claims 22 to 26, wherein said fracture proppant material comprises sand, and wherein said deformable particulate material comprises polystyrene divinylbenzene.

28. The composition or method of any one of the preceding claims, wherein said fracture proppant material and said deformable particulate material create multi-planar *in-situ* structures at said formation conditions of temperature and closure stress.

29. The composition or method of any one of the preceding claims, wherein no sticking or adherence occurs between said deformable particulate material and said fracture proppant material at said formation conditions of temperature and closure stress.

30. A composition for fracturing a subterranean formation substantially as hereinbefore described.

31. A method of treating a subterranean formation substantially as hereinbefore described.